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SAFETY MEASURES IN X-RAY WORK, INCLUDING HIGH-VOLTAGE FLEXIBLE CABLES.

By L. G. H. SARFIELD, M.Sc.(Eng.), Member.

(Paper first received 7th September, 1933, and in final form 1st December, 1933; read before THE INSTITUTION 22nd February, 1934.)

SUMMARY.

The paper opens with some information regarding conditions governing fatal injury due to electric shock.

Then follows a discussion of the electrical characteristics of the low-voltage circuits found in X-ray plant, and of the problems of earthing and safety in respect of supply potentials.

Reference is made to the presence of high-frequency currents in the primary circuit, and some suggestions are offered for the removal of their effects.

Some advantages and disadvantages of signal lights are mentioned.

The paper next deals with the secondary side of the X-ray equipment, and reviews the various voltages and typical circuits employed. A brief study is made of the possible shock effects due to three types of plant.

Safety measures are then considered in some detail. Arrangements for partial and total enclosure of dangerous components of X-ray equipment are examined, and instances are cited from commercial and experimental apparatus.

Examples of the use of high-voltage flexible cables in X-ray work are mentioned, and some characteristics of the cables are discussed. Particulars are given of methods of "making off" high-voltage cable ends.

Finally, some foreign safety regulations are reviewed; while in the Appendix an extract on the subject of electrical safety is quoted from the International Recommendations for X-ray and Radium Protection.

INTRODUCTION.

X-ray apparatus comprises two essential components; one is the X-ray tube and the other a generator of high voltage. Except in old-fashioned plant and certain experimental equipments the source of high voltage is a step-up transformer supplied from the mains either direct or through a rotary convertor. A system of valves or a mechanical device is employed (a) to rectify the transformer secondary current for passing it straight through the tube, or (b) to charge a bank of condensers which in turn supply the current through the tube.

Auxiliary apparatus includes insulated sources of current for heating the filaments of the X-ray tube and valves, high-voltage transmission with stabilizing chokes, resistances, instruments for measuring current and voltage, and a variety of devices incorporated in control gear to ensure easy manipulation.

It is proposed in this paper to consider the position in regard to safety from electrical dangers associated with the use of X-rays in the medical and engineering spheres, and to refer in some detail to the use of earth-sheathed flexible cables in X-ray work.

The development of safety features in medical plant has been very marked during the past 5 years. Also the Director of Radiological Research, Royal Arsenal, Woolwich, whose experimental work has been in pro-

gress since 1917 on the application of X-ray methods of examination to a wide range of Service problems, has devoted much attention to the question of electrical safety. X-ray equipment has been designed to be used by men having no scientific training and in dangerous locations. Apparatus has been installed and operated in shipyards and engineering shops. The rigid adherence to certain principles in connection with primary circuits, and proper design of the high-voltage system, have enabled X-ray apparatus to be placed with confidence—from a safety point of view—in unskilled hands. X-ray apparatus adapted to engineering requirements is now sold by commercial firms, and a number of examples of such apparatus will be mentioned.

In some instances the effect of high voltage alone is responsible for physical shock which may have serious and even fatal consequences. Generally, however, human contact with an electric circuit results in the flow of current in some part of the body, and under these circumstances, except for the case of high frequency, it is the amount of current which determines the danger.

The amount of current* which is dangerous is a variable depending on the person involved, the current distribution in the body, the condition of health, etc. Values from 20 to 100 mA are considered dangerous by various authorities, although still higher currents have not always proved fatal.

The voltage required to pass a given current through the body is a complex function involving the resistance of the body,† the area of contact, and the condition of the contact. Values of 1 000 to 3 000 ohms have been given by Nixdorf and Brandenburg for body resistance to direct current with extremities as electrodes dipped in water. Owing to polarization or electrolysis, resistance to direct current is greater than resistance to alternating current. The resistance of the body from hands to feet, the former being dry and the latter enclosed in leather footwear, has been given by Perussia as of the order of 50 000 ohms.

These figures suggest the conditions under which fatal currents may be passed through a victim, but only in a very general way; for fatal results have followed contact with a 40-volt circuit, and many accidents have been reported with domestic distribution systems, especially in bathrooms. With voltages upwards of 40 kV(P)‡ in

* See Reference (1).

† Most writers on this subject employ the word "resistance." Brazier [see Reference (20)] has given some data on the a.c. impedance of the body. Since a discharge circuit resulting from human contact with electrical apparatus generally incorporates contact resistance, insulation resistance, and body resistance (the latter comprising a small proportion of the whole), the pure resistance characteristics probably predominate. Resistance will be regarded as non-reactive in this paper.

‡ Throughout this paper kV(P), i.e. kilovolts peak, will be used to indicate maximum voltage.

use for energizing X-ray tubes, it is abundantly evident that grave dangers exist in apparatus which can supply the quantity of power corresponding to a fatal discharge.

The low-voltage or primary side and the high-voltage or secondary side of an X-ray equipment must each be regarded as an individual source of electrical danger. The characteristics of each will be considered separately. Some special instances will be given of the influence of the secondary on the primary and vice versa.

THE PRIMARY SIDE.

Most X-ray plants require alternating current for feeding transformers, and this is obtained at ordinary distributing voltages from domestic mains. If direct current only is available, inverted rotary convertors are employed. A few induction-coil equipments which require direct current are still in use.

In a typical installation the mains are linked to the apparatus through the usual intermediaries, namely the switch, fuse, and circuit breaker. Then follow tap switches, perhaps a foot switch, automatic timer, etc. In some types of plant, tap-changing and automatic devices may be served by contactors so as to avoid bringing power circuits to the control board, and this plan makes for greater safety. In most schemes the alternating mains voltage is brought to the control panel for some purpose or other. In many modern equipments the operating handles are of insulating material, and if live studs or contacts emerge from the face of the control panel they are covered by insulating material.

Earthing the Control Unit.

The question of the advisability of earthing control panels and frameworks is an important one which has been debated over a number of years.

Medical Work.—If the frame of the control unit be not earthed, it can, through some fault in the primary insulation system or accidental contact with a live lead, become live. Until the operator touches an earthed object as well as the live frame he is safe. Many wards and X-ray rooms have insulated floors, so that unless a radiator or similar earthed object be touched comparative safety is ensured from shock due to the primary circuit.

From the point of view of an operator at the control panel who may, while he is handling the controls or frame, inadvertently come in contact with a live lead on the high-voltage side of the equipment (assuming that the high-voltage side is accessible, as is sometimes the case), the fact that the panel fittings are not earthed is an advantage, since the high-voltage discharge has to traverse the resistance of the part of the body involved, and the insulation resistance of the controlling circuits and fittings, before it can reach earth by way of the primary circuit (which must be earthed somewhere on the system). The value of this advantage depends in part upon the quality of this insulation resistance, and it should therefore be of a higher order than that accepted for ordinary power circuits. Furthermore, everything accessible should be insulated, such as the sheathing of the cable flexibles to the portable control table, if this is being used. The fact that insulation which will with-

stand, say 2 000 volts for 1 minute, will generally withstand many times that value for 1 second without damage, is important in cases of short accidental contact. The danger attending accidental contact with the secondary circuit may be much reduced by good primary insulation.

Industrial Work.—Suppose that the operator is not protected by an insulating floor (this would probably be the case with industrial or other applications in an engineering shop) and is working with a control panel the frame of which is not earthed; the insulation of the control panel to earth would constitute a real danger if the panel were to become live owing to the failure of primary insulation. On the other hand the insulation of the panel to earth would offer no advantage to the operator, owing to his being earthed himself, in the case of accidental contact with an unprotected secondary high-voltage circuit.

When X-ray plant is used in industrial surroundings a control table approximates closely to a piece of portable electrical apparatus for engineering-shop use and, as such, should be subject to robust earth screening and reliable earth bonding. Also switchgear should be designed on the soundest lines, the earthable parts being effectually earthed and the live parts being well insulated. All flexible cables should be of the finest quality.

In an annual report* of the Chief Inspector of Factories and Workshops W. H. Swann, the senior electrical inspector, focuses attention on the general need of effective earthing. He states that switchgear below 650 volts was associated with the largest number of accidents, 3 fatal and 82 non-fatal being attributed to this class of apparatus. Cables and flexibles came next with 4 fatal and 40 non-fatal; plugs and adaptors with 1 fatal and 21 non-fatal; and portable electrical machines with 3 fatal and 13 non-fatal. Of 22 fatalities in factories, 14 occurred at 200–250 volts alternating current. Kouwenhoven and Langworthy† have stated that 2 500 persons suffer annually as a result of contact with electrical circuits in the United States, 50 of whom die from electrical causes in general and low-voltage circuits in particular.

While it is realized that X-ray equipment has had comparatively small commercial application in factories as yet, the use of X-ray methods of examination of materials is increasing and it is important to utilize the experience gained in other branches of electrical work.

The fact that low-voltage flexibles are used for foot switches, trailing pilot leads, and the like, in medical and engineering X-ray apparatus, means that such flexibles are liable to receive heavy wear and tear. There is therefore a possibility of insulation breakdown and, if the operator is earthed, the risk of dangerous contact with the electrical circuit. In addition to the use of high-grade insulation, careful wiring, and sound earthing, for ensuring greater safety, there remains the alternative of adopting voltages lower than mains voltage for all control circuits. This latter plan has been suggested for increasing the safety of electrically-operated tools and seems quite appropriate to X-ray plant, especially that required for engineering applications. The fact that auto-transformers are so frequently found in X-ray

* See Reference (2).

† *Ibid.*, (3).

primary circuits makes it a comparatively easy matter to utilize a low-potential tapping for control purposes.

The ideal in the matter of control of apparatus for industrial work is perhaps realized by the termination of all circuits beneath the face of the operating panel and the provision of earthed mechanical linkage between movable parts, such as switches, and the necessary handles. The panel can then be an earthed plate drilled and labelled to suit the fittings. This scheme was adopted for the supply circuits of a 400-kV(P) set at Woolwich, and it could be fairly cheaply applied to apparatus of all ratings.

It is of utmost importance that the enclosing framework of the control unit be adequately earthed and that all parts intended to be earthed be well bonded together. The fitting of instruments to an earthed control-panel need not introduce any discontinuity of conductivity, for instrument glass* can now be obtained which will not hold a charge.

At least one sound earthing point† should be available in every X-ray bay or enclosure. If a main water supply is not accessible for the purpose, special earthing strips made of 1 in. \times $\frac{1}{8}$ in. copper, as short as possible, should be carried to an earthed pipe or plate (or series of pipes or plates, according to the conductivity of the earth) well embedded in the earth. For a radiological department such strips should be run throughout the department so that attachments to them can be made from any operating point. Earthing to a building stanchion is not generally recommended, for there is the danger that instead of removing charges the stanchion footings may distribute them. These footings may vary in resistance, and the values are seldom small enough to warrant their use for earthing purposes.

An interesting case illustrating the need for short, direct earth leads was provided when radiological examination of an airship was made by the Director of Radiological Research, Woolwich Arsenal. The X-ray equipment comprising a self-rectifying X-ray tube, 70-kV(P) transformer, and control gear, was carried up into the ship. Earthing was first attempted by connecting to the steel framework of the ship, which was itself earthed at 6 points distributed along its 700 ft. of length. The result of this was that small high-frequency discharges could be drawn by the hand from the framework within a large area surrounding the point of operation of the set. The earthing system was probably behaving as an aerial, picking up oscillations generated in the high-voltage transmission to the X-ray tube. Independent earthing leads had to be employed to eliminate the trouble.

Experiments have shown that it is possible to draw sparks $\frac{1}{2}$ inch or more in length from a poorly earthed wire hung up near a mechanically-rectified high-power X-ray generator which is in operation.

High-Frequency Effects.

A characteristic of X-ray apparatus which is not common to ordinary electrical equipment for domestic and industrial use is the possibility of the presence of

high-frequency currents in the primary circuits. These high-frequency currents are received from the secondary side, either by aerial pick-up or by capacitance coupling of the primary to the secondary, and they have been observed in valve-rectified as well as in mechanically-rectified apparatus. The effects are, however, generally of greater magnitude in apparatus fitted with mechanical rectification. Whatever the source of these oscillations, precautions must be taken for getting rid of them since they may lead to dangerous discharges.

If the primary wiring and connections are all well screened from the operator these effects constitute no danger to life, but they will weaken insulation so as to permit high-frequency discharges, which may be followed by a power burn-out. The safety of the set is thus involved, and the result might mean putting the equipment temporarily out of commission even though the fuses or circuit breakers prevent serious damage. Familiar points at which charges build up and discharges appear are instrument and other inductive windings, hold-on coils, etc. An advantage of the use of contactors is that the X-ray transformer primary circuit need not be brought to the control panel.

A remedy which has been applied in the Research Department, Woolwich, is the connection of centre-earthed condensers across primary circuits liable to be affected. This remedy is one commonly adopted for protecting windings of instruments used in X-ray work. Small capacitances of the order of $0.01 \mu\text{F}$, insulated for ordinary power voltages, serve admirably. Wireless-type condensers have been used with success. Connected across the main pair of leads from the X-ray transformer to the distribution or control panel two $0.01 \mu\text{F}$ condensers in series, with the junction earthed, will often take care of the trouble. Additional pairs across hold-on coils are sometimes advisable. It is helpful also to enclose primary leads in earthed sleeving in cases where they traverse high-frequency fields.

Signal Lights.

The use of signal lights demands careful attention, since it is so easy for the meaning of certain lamps to be misinterpreted.

A lamp is often mounted on a control panel to indicate by its light that the board is live. In many installations the main switch is remote from the control panel, especially when the latter is movable. Closing the main switch makes the voltage available at the panel, and this is conveniently indicated by a lamp which may be green, or, if intended for instrument illumination, white. A further lamp (red) is then useful to indicate when the X-ray transformers are excited, that is, when there is a likelihood of high voltage being on the set. The red lamp would be ideally connected across the primary terminals of the X-ray transformer if it were not for the fact that this may be operated at a variety of voltages, which would result in the lamp having variable brightness, sometimes no light at all being discernible. Removal of the lamp to the supply side of the auto-transformer would only be permissible if the load side of the latter were always connected to the X-ray transformer when the auto-transformer was excited. This is not always the case.

* See Reference (4).

† For recommendations in regard to reliable earthing, see P. D. MORGAN and H. G. TAYLOR: "The Resistance of Earth Electrodes," *Journal I.E.E.*, 1933, vol. 72, p. 515.

A system which can be employed when contactors control the X-ray transformer primary is to connect a low-voltage signal lamp in series with the hold-on coil of the contactor switch, so that when the coil circuit is made the light comes on. If the lamp burns out, the coil cannot be excited and the contactor will not close the transformer primary circuit.

A criticism applicable to this arrangement as it stands is that, in the event of a contactor switch sticking in, absence of the red light would not indicate safety. A combination of a danger signal and a safety signal, however, offers the essential features required for informing an operator of the condition of his set. Thus a red lamp may be connected in the hold-on coil circuit of the contactors energizing the X-ray transformer, and a green lamp may be connected in an independent circuit closed and joined to the supply by contacts brought together when the contactors are in the open position.

Under these conditions, the indications of the red and green lamps would be as follows:—

Red lamp only: danger, X-ray transformer energized.

Green lamp only: safe, X-ray transformer dead.

No lamp on: caution, contactors may be stuck in with their hold-on coils dead.

The white lamp mentioned first would still indicate the presence or absence of power on the board.

Lamps are used on commercial X-ray equipment to indicate the excitation of a variety of parts of the primary system. In one case, for instance, a red lamp lights up when the time switch comes into operation. This time switch operates the X-ray transformer primary. No signal is provided to indicate the completion of the high-voltage transformer circuit, nor is there any alternative to indicate safety if the red lamp does not light up.

Concerning personal safety from electrical dangers, warning lamps are really most important when the apparatus has parts operating at high voltage which can be touched at will. Apparatus totally enclosed in earthed sheaths does not require indicating signals except to advise an operator that power is on, to show a possible emergence of X-rays, and to give warning against wasting of electrical power. Some operators prefer not to have any signal lights at all, whatever type of apparatus they use. It is felt that if signal lights be used to show the presence or absence of danger it should be possible to devise some foolproof code which would be both positive and simple.

Audible signals are also used, but these generally require manual operation. Automatic characteristics are not easy to apply, and noises are liable to upset a patient. Some safety instructions (e.g. the German Rules for High-Tension Protection in X-Ray Apparatus*) state that audible or light signals must be used. In the author's opinion, if signal lights are recommended there should also be a recommendation as to how they should be employed and some code to indicate safe or caution conditions of the apparatus.

THE SECONDARY SIDE.

We have already stated that fatal accidents have been known to occur as a result of quite low voltages, and we

have noted some important points governing the safety of primary circuits in respect of their own potentials. We have also noted for different arrangements of control apparatus some of the conditions existing in the event of an operator's accidental contact with the high-voltage circuit.

The range of secondary voltages employed in X-ray work and the various circuits generally associated with particular voltages will now be considered, and observations will be made regarding the comparative dangers of some of them.

Voltages Appropriate to the Various Medical and Engineering Applications.

In the medical sphere the voltages chiefly used are: 60 kV(P) for bedside and portable work, 90 kV(P) for general radiography, 120–150 kV(P) for screening and treatment (deep therapy), and 180–210 kV(P) for X-ray treatment.

These figures represent no hard and fast rules. Radiologists have their own preferences in point of suitable voltages for their work, and manufacturers produce equipments of various ratings. The standard secondary voltages for X-ray transformers recommended by B.S.S. No. 326—1928, are 60, 90, 120, 150, 180, and 210 kV(P). Some specialist radiologists in this country employ voltages up to 350 kV(P) for experimental purposes, and Continental manufacturers have made apparatus for 400 kV(P) for use in radiological institutions where special facilities are available for research. In the Memorial Hospital, New York City,* there was installed in 1931 a 2-section X-ray tube operating at 900 kV(P). Most ordinary medical radiology is at present done within the limit of 0–150 kV(P); and most treatment within the limit 0–200 kV(P). The same range of voltages is useful for engineering applications of X-rays. A great deal of spectroscopy is done within the 65-kV(P) range, while Laue spot radiographs are successfully obtained in the region of 100 kV(P). Metal radiography up to the penetration of 3½ inches of steel can be performed at 200 kV(P), while many specimens in "transparent" materials such as aluminium may be examined with much lower voltages. The higher figure is the "general utility" value for this branch of work. Voltages up to 400 and 500 kV(P) are becoming common in experimental establishments, and indeed reports have been published of radiography at 2 000 kV(P) in the U.S.A., but for commercial plant now being introduced for X-ray work in industry the appropriate voltage is 200 kV(P).

In the Table on page 257 the characteristic types of circuits for a variety of voltages are shown, together with typical diagrams of connections. Although not included in the Table, 3-phase 6-valve circuits and simple condenser discharge connections are also employed in certain modern X-ray equipments.

The induction coil is still in use in some medical establishments for routine work, but in this sphere it does not represent modern practice. Special induction-coil outfits have been developed for experimental work and it is therefore impossible to ignore this type of plant. Coils are, however, in a class by themselves.

* See Reference (5).

* See Reference (6).

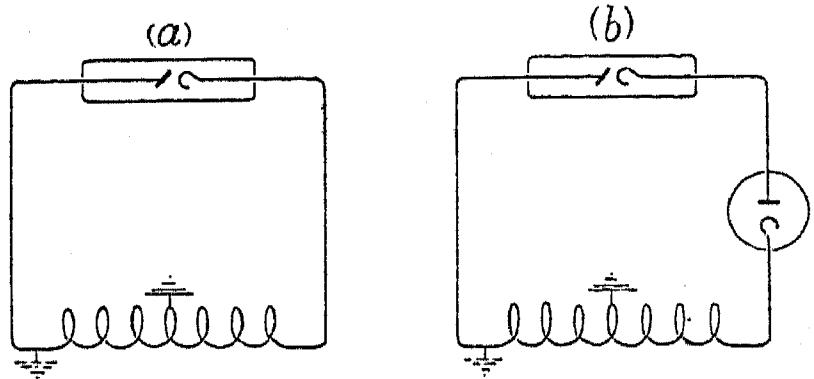
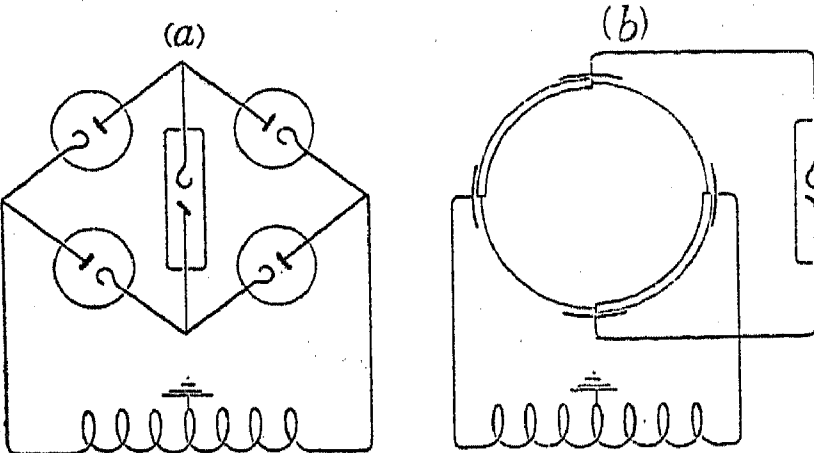
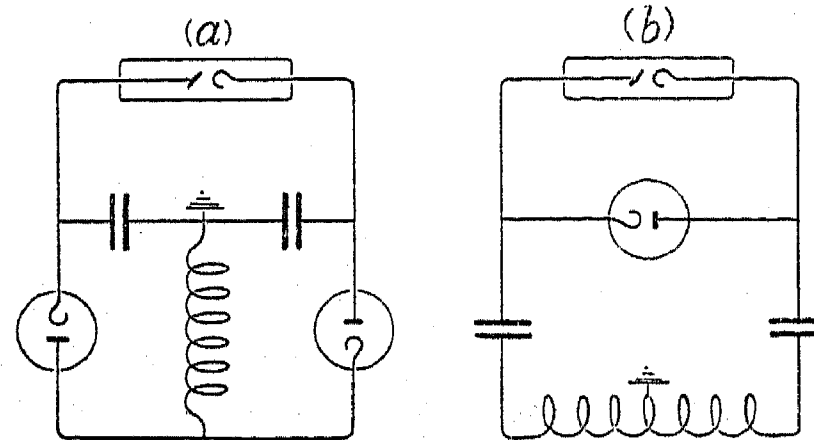
Some Characteristics of Various Kinds of Plant.

It is commonly believed that the higher the voltage the more dangerous the apparatus. In certain respects this is true, but the fact that fatal accidents have occurred in connection with the simplest devices makes it necessary to specify conditions before such a principle can be accepted. It will be assumed that all the voltages used on the secondary side of X-ray apparatus are equally dangerous if the operator comes into contact with live conductors, and that normal working clearances are proportionately increased with the rise of voltage, so that different types of equipment may be compared from the point of view of circuit and power characteristics. The

Accidental contact of a person with a live lead is generally regarded as the earthing of that lead through a non-reactive resistance which may have a very high value and consist, for instance, of the resistance of the body and clothing, or the resistance of the body and the insulation resistance of the primary control circuits.

The physical effects of the current depend on its amount and the duration of its flow. The current in turn depends upon the voltage and the resistance. Now with different equipments the voltage is applied for different periods of time. Typical potential wave-forms on open circuit or at small loads (Fig. 1) show that the proportion of the period during which voltage is applied

TABLE.

	Voltage, kV(P)	Type of circuit	Typical connections
1	60-90	Transformer with:— (a) X-ray tube as rectifier or (b) Additional rectifying valve.	
2	120-150	Transformer with:— (a) Full-wave valve rectification or (b) "Chopped" full-wave mechanical rectification.	
3	180-210	Transformer with valves and condensers for approximately doubling transformer voltage at tube:— (a) "Constant-potential" Greinacher circuit. (b) "Pulsating - potential" Villard circuit.	

author has not discovered any information regarding the time required for dangerous muscular reactions to occur, except in the general way that high-frequency energy is not usually dangerous whilst low-frequency is. The wave-form of the supply probably also has a bearing on physical effects.

It has been said that induction coils are the least dangerous, condenser sets come next, and rectified transformers are the most dangerous of X-ray equipments. Very little experimental data is available on the question. It may therefore be worth while very briefly to notice the characteristics of various circuits. Only broad observations will be made, as it is impossible without a much more detailed investigation to assess the importance of the variety of characteristics corresponding to coils, transformers, etc.

to the load is shortest in the case of coil and longest in the case of constant-potential equipment. This would suggest that the constant-potential equipment is most dangerous, since a high percentage of the voltage is available for a large proportion of the time. The voltage characteristic of each equipment under heavy-load conditions, such as would be imposed by accidental human contact with the high-voltage circuit, is, however, the important thing.

Let us therefore examine the conditions for an induction coil, an ordinary rectified transformer set, and a constant-potential plant.

Although the resistance of the combination of body, clothing, and primary insulation, may be greater or less according to circumstances, we will assume that 1 megohm represents the resistance to earth under

average conditions of human contact with a high-voltage lead. The body resistance represents but a small proportion of this. Let the contact be made at a point near the tube, i.e. after rectifiers and condensers.

Induction coil.—If one end of the coil were earthed in this way the potential of the other end would tend to rise and a spark to earth at that end would be likely to occur. If the spark were of low resistance the voltage of the coil would be transferred to the human contact-resistance system and current would flow. This current

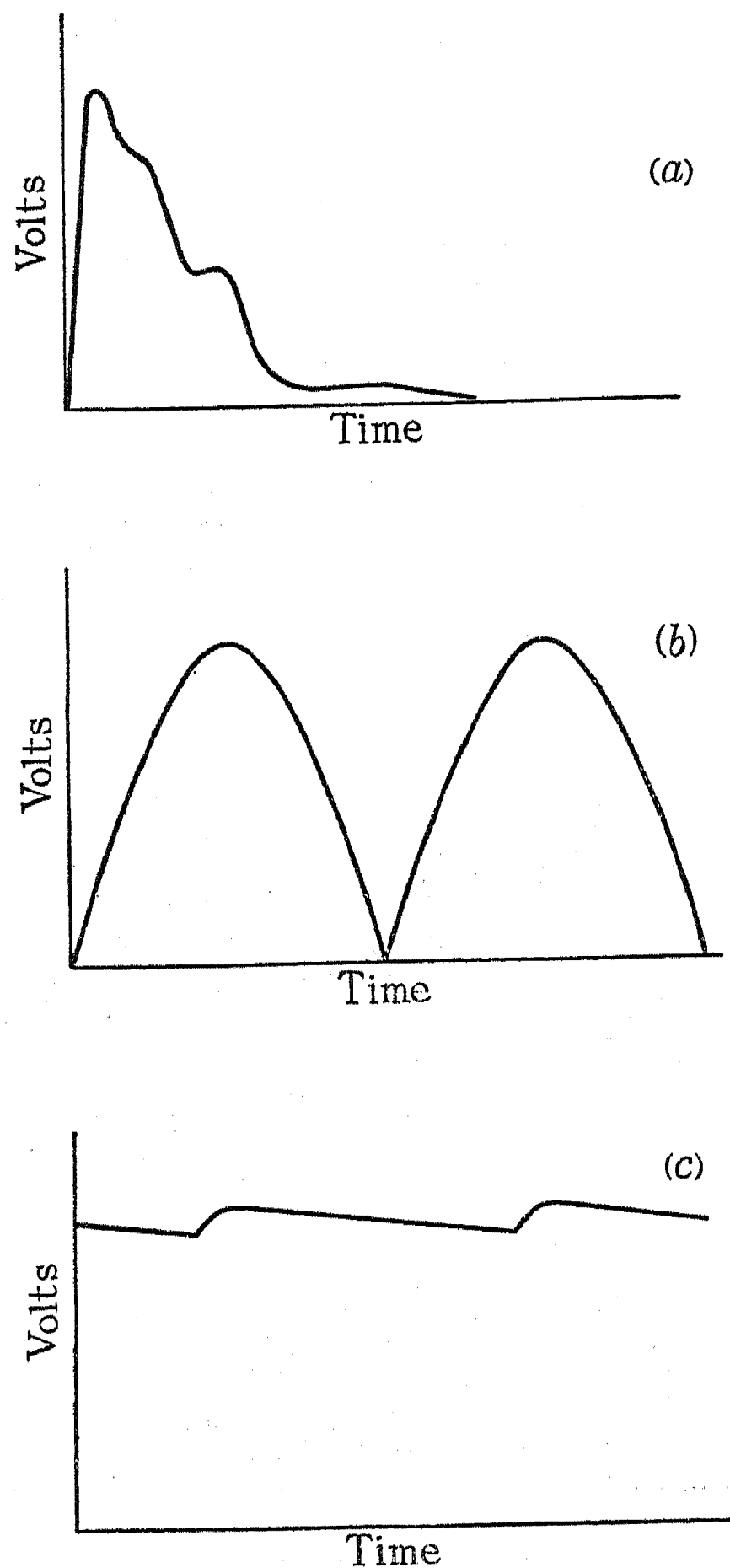


FIG. 1.—Open-circuit or light-load wave-forms.

(a) Induction coil. (b) Rectified transformer. (c) "Constant potential."

would reduce the voltage. Taylor-Jones* has shown that the connection of a 1-megohm resistance across the induction coil reduces its voltage to 0.36 of the open-circuit value. Fig. 2A† shows an induction-coil secondary voltage wave-form when still smaller resistances are connected.

The collapse of the voltage is striking. Fig. 2B† shows how the ratio of short-circuit to open-circuit peak voltage varies with resistance connected across the secondary.

Transformer and Rectifier.—In a transformer having its centre-point earthed and full-wave 4-valve rectification [see 2(a), in Table] the voltage would be of the normal wave-shape but would be depressed below the open-circuit value to an amount depending upon

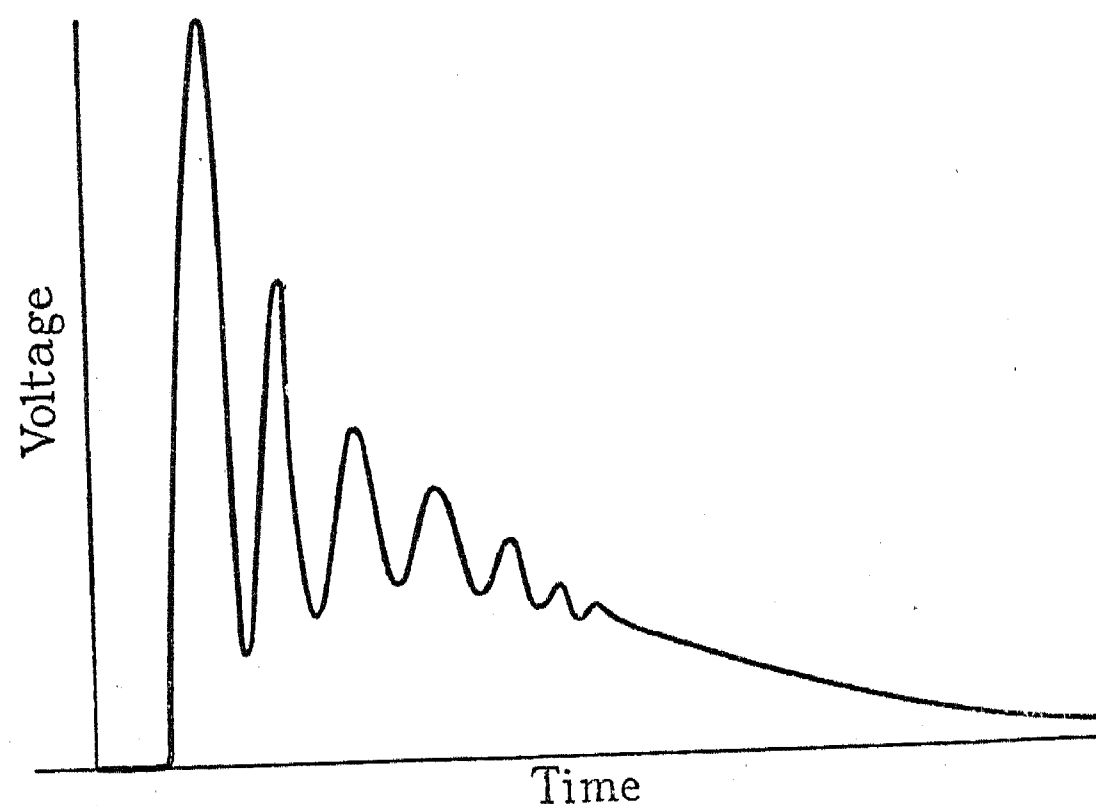


FIG. 2A.—Secondary-voltage wave-form of 12-in. induction coil with 0.1 megohm across secondary winding.

the load. The maximum current through a 1-megohm earth for a 100-kV(P) transformer would be $5 \times 10^4/10^6$ amp. = 50 mA. Since modern X-ray transformers are designed for loads much greater than 50 mA without undue voltage-drops, the condition imposed by the earth would not represent a serious load. The actual drop in

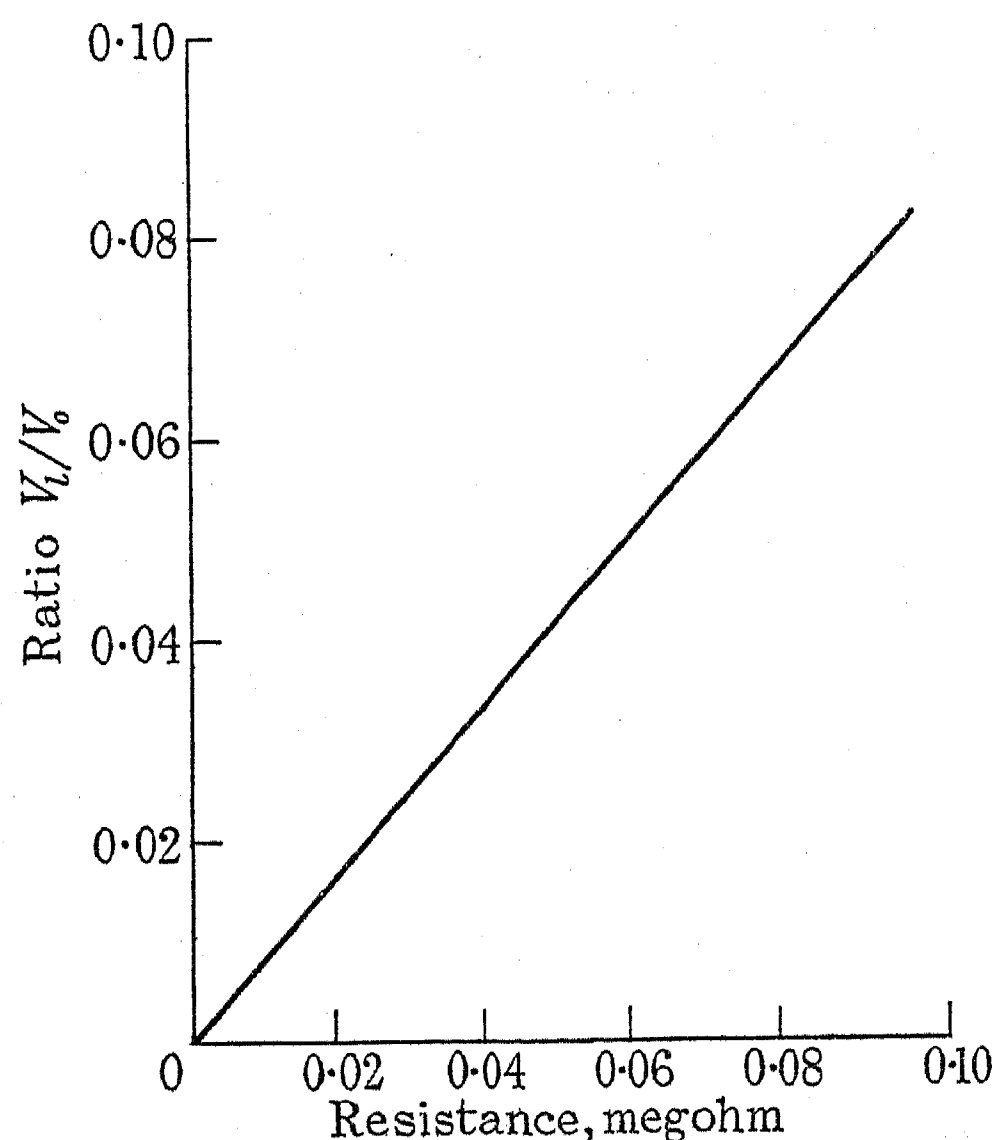


FIG. 2B.— V_i/V_o = ratio of coil secondary-voltage with resistance across it to coil secondary-voltage on open circuit (peak values).

any particular instance would depend largely on the method of voltage control in the primary, which could, in the case of primary regulation by auto-transformer and resistance, for example, impose a loss of voltage external to the transformer itself. Nevertheless, a high proportion (up to 70 per cent, say) of the total voltage remains as a very potent source of danger. The case

* See Reference (7).

† For both of these figures the author is indebted to Mr. W. McFarlane of Glasgow University.

of single-valve half-wave rectification varies very little from that of the full-wave, but the voltage frequency is half in the latter case of what it is in the former. When a mechanical rectifier is employed there are definite periods when the tube is disconnected from the high-voltage generator. At such periods in every cycle only the current due to the capacitance of the high-voltage circuit would pass through the resistance earth.

Constant-Potential Equipment.—Let a valve-fed constant-potential set [e.g. 3(a), in Table] have a total capacitance of $0.005 \mu\text{F}$ across the high-voltage line, that is, $0.01 \mu\text{F}$ between each line and earth—a common value for sets required to deliver small loads. Suppose the capacitance is charged up with 50 kV(P) per condenser, that is, 100 kV(P) overall, and a 1-megohm earth is connected to one line. A load of 50 mA would commence to flow. Let C = capacitance of one side to earth = 10^{-8} F ; i = discharge current = $5 \times 10^{-2} \text{ amp.}$; t = time in seconds; and V = voltage drop.

Then $i = CdV/dt$, and voltage drop per second = $dV/dt = i/C = 5 \times 10^6 \text{ volts.}$

Total voltage drop in $1/100 \text{ sec.} = 5 \times 10^4 \text{ volts} = 50 \text{ kV.}$ Thus the voltage of one side would tend to drop to zero in $1/100 \text{ sec.}$; but this voltage drop is further controlled by the transformer. If the condenser were being charged by alternate half-waves, and the contact were made during one of the non-charging half-waves, collapse of the voltage would occur. If, on the other hand, a contact were made during a charging half-wave the discharge through the human-contact earth would follow the transformer wave, and the conditions would be similar to those with the plain transformer set.

This brief analysis confirms first that there is a minimum of danger associated with the induction coil due to the collapse of its voltage on heavy load, and second, that very great danger may be expected of the plain transformer set owing to the maintenance at high loads of so great a proportion of the maximum voltage. In addition, it suggests that the transformer backing of a condenser set renders it also a very dangerous type of apparatus.

Although danger of greater or less degree may be associated with different types of X-ray apparatus, the only positive way to deal with the matter is to consider all apparatus as requiring definite safety provisions.

Tripping Gear Operated by Accidental Earth.

Before the screening of high-voltage apparatus is dealt with, mention should be made of a device which can be fitted to an existing equipment for the purpose of tripping out the supply to an X-ray plant should accidental contact be made with its high-voltage circuit.

This instrument, called the "Salvator," comprises a very sensitive relay and an auxiliary relay. The coil of the former is connected between the centre point of the X-ray transformer and earth. Normally the coil carries no current. When a part of the high-voltage circuit is earthed (as may be the case if a live wire is accidentally touched), current immediately traverses the coil, attracting an armature, and resulting in the operation of the auxiliary relay, which trips a double-pole circuit breaker in the transformer primary. A diagram of connections is shown in Fig. 3. It is recommended by the manu-

facturers that the device be tested every day, and for this purpose a high resistance is provided which can be connected between one high-voltage lead and earth to simulate the conditions of human contact. This accessory is mounted in a bakelite sleeve and has a resistance of 50 000 ohms. It is important also to see that there remains after use no pitting or burning of the automatic circuit-breaker contacts such as would tend to make their action sluggish.

Some years ago the Victor Corporation of America developed a safety device for the same purpose as that described above, and many tests on human beings with the instrument gave evidence of its satisfactory performance. It was decided, however, not to put the device on the market but to concentrate instead on the production of an X-ray equipment in which it would be

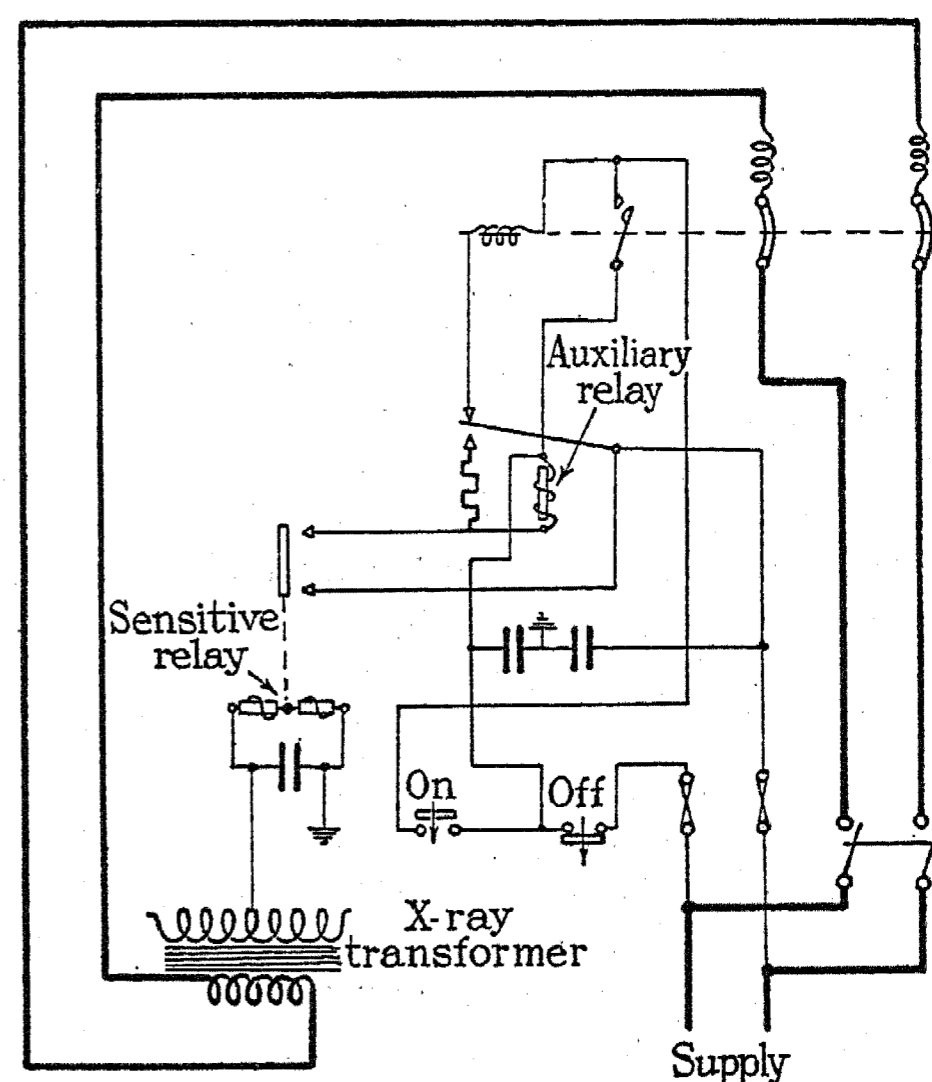


FIG. 3.—Diagram of connections of the "Salvator" (Pilon), a device for tripping the high-voltage transformer out of circuit in case of accidental contact with a high-voltage lead.

impossible to make accidental or intentional contact with the high-voltage system. This equipment is considered in the next section of the paper.

The Screening of High-Voltage Parts of X-ray Apparatus.

There still remains in use in hospitals X-ray equipment for visual and radiographic work at 100 kV(P) or thereabouts in which little more than the transformer and rectifying apparatus is enclosed, the bare high-voltage leads being brought to the X-ray tube without any protection other than that afforded by judicious positioning. If these high-voltage leads have to traverse the room they are raised to a height of 9 feet in compliance with the International Safety Recommendations, but at the point of junction with the tube the leads approach both patient and operator within dangerous limits.

In some of the more modern apparatus the old overhead system has been retained, but a variety of guards have been introduced for use at the X-ray tube and—in the neighbourhood of the patient—around the high-voltage leads. Until a few years ago many British manufacturers adopted this scheme. These guards have

taken the form of earthed cages of expanded metal (the mesh sizes are specified in some safety recommendations), insulating cylinders, or barriers, encircling or partially encircling the tube. The leads passing to a tube mounted underneath a couch would be enclosed in insulating casings with or without earth sheathing. It is important that protective measures should not forbid mobility of the tube.

An up-to-date medium-voltage [90 kV(P)] lay-out for visual and radiographic work which is utilized by two Continental firms provides for the assembly of the whole of the electrical apparatus, with the exception of the control panel, in an enclosure with one wall forming a panel against which the patient stands and parallel to which a viewing screen may pass up and down. The X-ray tube inside the enclosure is mounted so that it can also move freely in a plane parallel to the panel wall, and the tube movement is controlled externally. In one instance this movement has been provided by electrical means, a system of contacts being operated by a "joy-stick" similar to an aeroplane control column. The contacts energize motors which provide vertical or horizontal motion, so that the whole screen field is covered by the tube.

In high-voltage work for therapeutic treatment and metallography at 200 kV(P) and over, it has for many years been the practice to enclose the X-ray tube in an earthed container of rectangular or cylindrical shape. Such a container could be let into one wall of the protective enclosure in which the apparatus is housed, and thus provide excellent security from electrical danger. A container of this sort, however, incorporating a large amount of sheet lead for ray protection, is cumbersome and generally difficult to move except on its own axis. In an American design this is done by mounting the cylinder on rollers fitted in a gantry directly over the couch, but this scheme necessitates means for moving a patient or specimen with reference to the tube, instead of vice versa. As a result of this necessity, couches for radiographic treatment were developed which could be raised or lowered and traversed underneath a fixed X-ray tube in a protective box.

An important development in 1926 of the large protective box for high-voltage tubes took the form of the "cannon" equipment. In this arrangement the tube was mounted in a large earthed lead-sheathed cylinder designed to project (like a cannon) through a wall into the X-ray room, all the transformers and high-voltage equipment being housed on the remote side of the wall. The operating panel was assembled in the X-ray room and every advantage taken of remote-control devices. The cannon could move upwards and downwards, and the tube could be rotated on its own axis. The tube was worked at a maximum of 200 kV(P).

All leads, instruments, and connections, of high-voltage circuits which are exposed to the air in an X-ray operating room should be of ample radii so as to reduce corona discharge to a minimum. In addition, the matter of ventilation should be carefully attended to, as the ozone and nitrous oxide generated in highly stressed air produce nausea, headache, and other depressing effects. The International Recommendations for X-ray and Radium Protection state that all rooms should be provided with

adequate exhaust ventilation capable of renewing the air of the room not less than 10 times an hour. Air inlets and outlets should be arranged to afford cross-wise ventilation of the room. In the Research Department, Woolwich, there has been installed a special system of ventilating conduits linking up all rooms in which there is the possibility of high-voltage apparatus contaminating the air, and an exhaust fan is in constant operation to ensure that the air is frequently changed.

Total Enclosure of Tube and Generator in One Common Earthed Portable Container.

The very sound principle of achieving electrical safety by enclosing the whole of the apparatus except the control panel and supply circuits in earthed screening has formed the basis of all modern safety X-ray apparatus. One outcome of its application is the enclosure in one common container of the X-ray tube, transformers, and other details, affording complete freedom from external electric field. The advantages of this scheme, together with those of oil immersion with consequent reduction of dimensions, were utilized in 1920* in the design of the Coolidge dental X-ray outfit. This unit was marketed in 1923. Meanwhile the idea of oil immersion of the X-ray tube alone had been used by Pilon of Paris for high-voltage work.

This scheme was extended in the design developed in the Research Department, Woolwich, for a medium-power plant to be applied to X-ray examination of materials employed in aeroplane construction. The plant† made use of a universal Coolidge tube and kenotron rectifier connected in series across the secondary winding of an X-ray transformer. Separate heating transformers were used for the filaments of the rectifying and X-ray tubes. The whole was oil-immersed in a lead-lined tank 3 ft. × 2 ft. 7½ in. × 2 ft. 2 in. having an adjustable diaphragm for the emergence of the rays. The set was supplied at 200 volts, and, although normally operated at 110 kV(P), the transformer could deliver 10 mA at 140 kV(P) continuously.

In 1929 the Victor shockproof apparatus for general radiography made its appearance. This is also a complete X-ray generator oil-immersed in an earthed metal tank, having heat-radiating fins. It comprises a 90-kV(P) transformer and specially designed X-ray tube, which is of the self-rectifying oil-immersed radiator type with cathode and anode axes at right angles. The size of the tube head is about 15 in. × 12 in. × 12 in., and its weight about 140 lb. This weight is, of course, counter-balanced when the head is assembled on the supporting stand. The expansion and contraction of the oil due to load heating are compensated for by means of bellows which operate automatically according to the oil volume. This totally enclosed unit has freedom of movement in every required direction, and can be passed under or over a couch or used in conjunction with a vertical fluorescent screen.

A much larger equipment for radiographic examination of welds on a very large scale (Hoover Dam Penstocks) has been recently developed by the same firm. This equipment (illustrated in Fig. 4) comprises an X-ray

* See Reference (8).

† *Ibid.*, (9).

tube, an X-ray transformer, rectifying valves, filament heating transformers, and condensers. The tube has a circulating oil system for anode cooling and is rated at 300 kV(P), 10 mA. The whole is immersed in oil in a steel tank provided with a window arranged to permit X-rays to emerge. Only two low-voltage leads are taken to the tank, which has very free movement in many directions; the control table is located within the operating cubicle.

Details have already been published* of a complete X-ray equipment, transportable and enclosed in earthed

is not resorted to for reduction of dimensions. Economy in space is, however, effected in other novel ways.

One instance is the Demophos, a German equipment (shown in Fig. 5) in which the Villard circuit is employed. In the Villard circuit [see 3(b), in Table], an arrangement for approximately doubling the transformer voltage, a condenser is interposed on each side between the transformer secondary and the X-ray tube, across which a valve is connected in parallel opposition. In this particular apparatus the valve and X-ray tube are combined in one envelope, as shown in the figure, while the condenser is

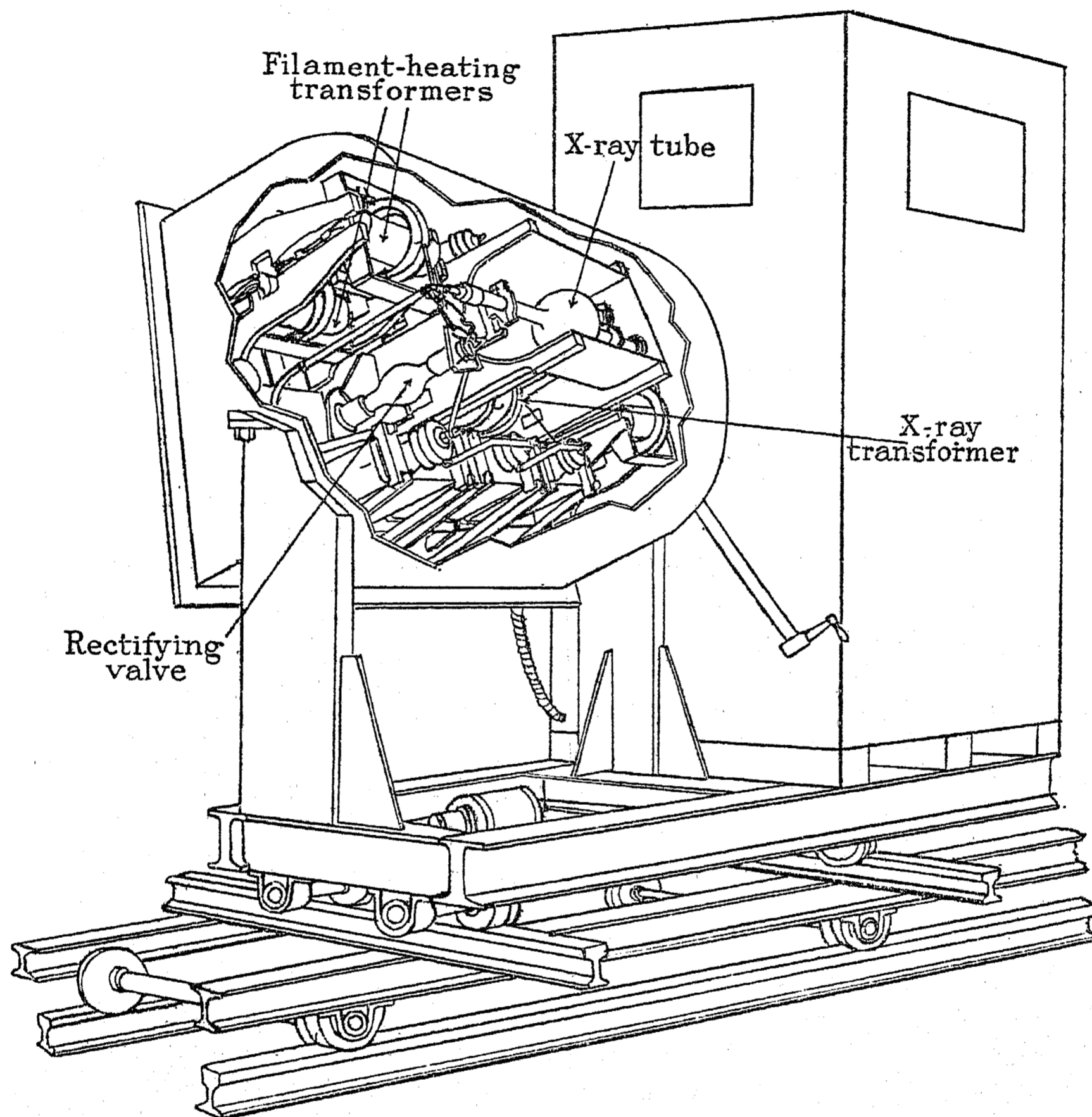


FIG. 4.—View of 300-kV(P) X-ray equipment for examination of welds, showing arrangement of earthed casing, the control cabin, and travelling gear.

metal, which was designed and constructed in the Research Department, Woolwich. The metal case of this 200 kV(P) apparatus consists of panels firmly linked together, and it is impossible to gain access to the high-voltage equipment without unlocking the panels, or to the X-ray tube without opening the circuits, which must be closed before the transformers are energized. This unit has been used extensively for metal radiography in dockyards and engineering shops in England and Scotland.

There are a number of modern examples of earth enclosure of complete equipments in which oil immersion

is not resorted to for reduction of dimensions. Economy in space is, however, effected in other novel ways.

Another example is afforded by a Continental apparatus for 200 kV(P), which was exhibited in connection with the International Congress, Paris, 1931. In this case the tube and high-voltage generator are housed in a large U-shaped container attached to the ceiling in the X-ray room. In the fixed vertical limbs of the U are accommodated the components of the high-voltage generator, while the horizontal portion, which

* See Reference (10).

can turn on a horizontal axis, contains the X-ray tube. This scheme effects a great saving of space for the kind of apparatus that it represents, but, like the "cannon" design, it is of a ponderous type, which is being departed from in some of the newer apparatus designed to give electrical safety.

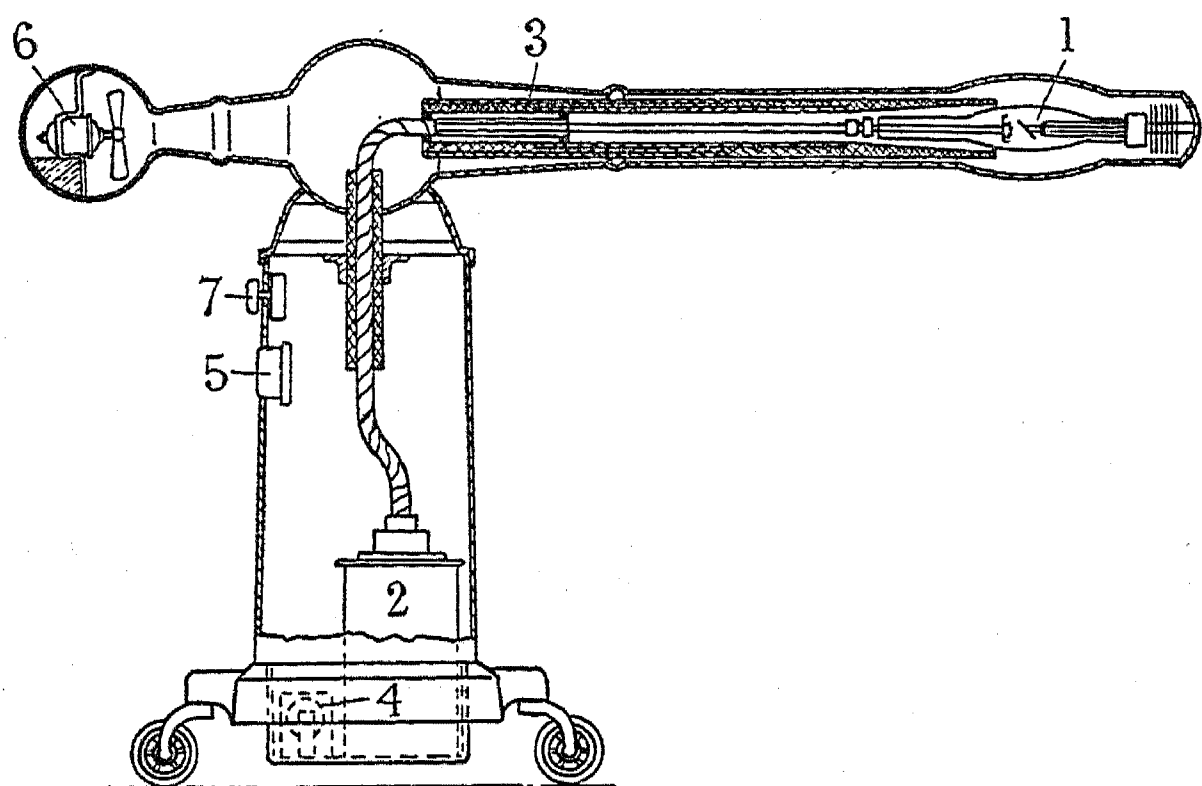


FIG. 5.—Mobile X-ray equipment for 80 kV(P), totally enclosed in earthed metal (Siemens).

1. Combined valve-X-ray tube.
2. High-voltage transformer.
3. High-voltage condenser.
4. Low-voltage filament-heating transformer for the valve.
5. X-ray tube milliammeter.
6. Ventilator.
7. Main supply leads.

Earth-Sheathed X-ray Tubes and High-Voltage Leads.

As an alternative to the enclosure in one comprehensive casing of the complete X-ray outfit, there is the plan of utilizing an X-ray tube sheathed in earthed metal and connected to the generator by means of earthed sheathed cables. This permits the high-voltage plant to be located in almost any convenient place, while the tube can be close to the patient or object under examination. The scheme also allows existing sets to be employed with the new shockproof tubes. The X-ray tube itself,

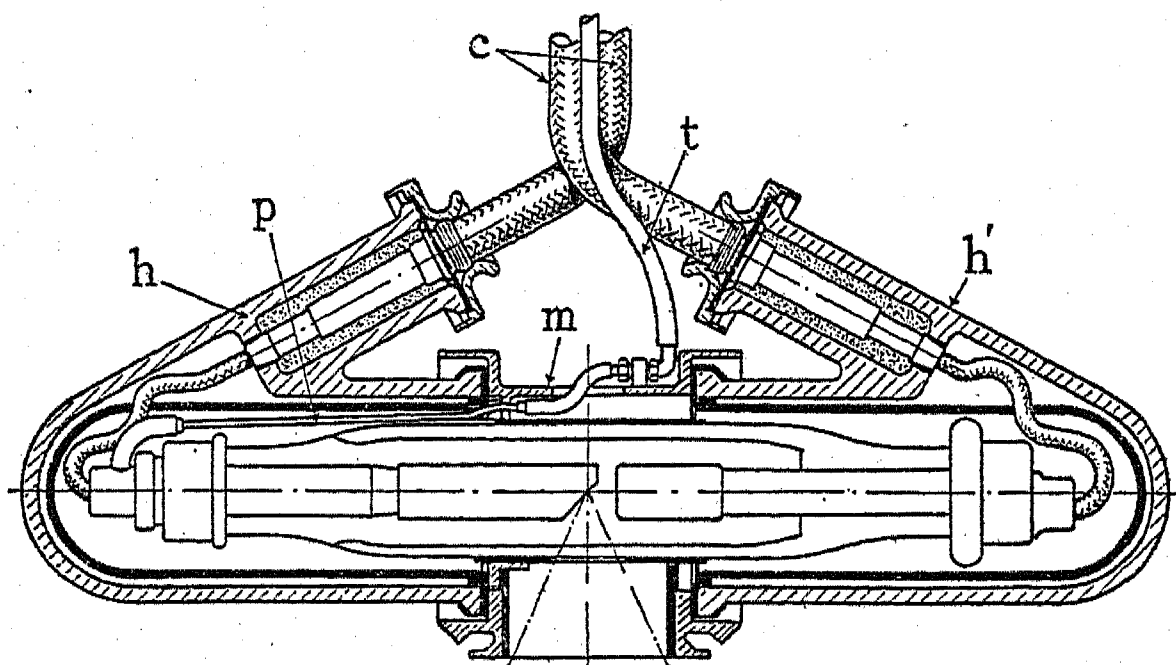


FIG. 6.—"Tuto" shielded X-ray tube fitted with earth-sheathed cables.

though housed in its earthed casing, is generally a smaller item than the assembled tube and apparatus considered above (this is particularly the case in the 200 kV(P) class), but there remains the slight disadvantage of restriction of mobility offered by the cables. This effect is considerably diminished, although not negligible, when proper cable-supporting arrangements are made.

There are isolated cases of the use of high-voltage

cables as components of X-ray apparatus dating back a number of years, but it is only very recently that they have been adopted to any considerable extent. High-voltage cables will be considered separately in a later section of this paper.

The Metalix Junior was the first commercially available shockproof portable set comprising a transformer and complementary fittings enclosed in an earthed vessel, an earthed metal-sheathed ray-protected* X-ray tube and earth-sheathed high-voltage leads joining the two. The metal sheathing is an integral part of the tube. In this unit (Patent No. 295028—1929) the tube operates at 47 kV(P) and has a useful range of medical and spectroscopic applications. The high-voltage cables are permanently fixed to the tube and can be easily inserted in sockets in the transformer. Not until the cables are thus in position, completing the earthed-metal screening, can the transformer be energized, nor is it possible to remove them unless the current is switched off. Thus

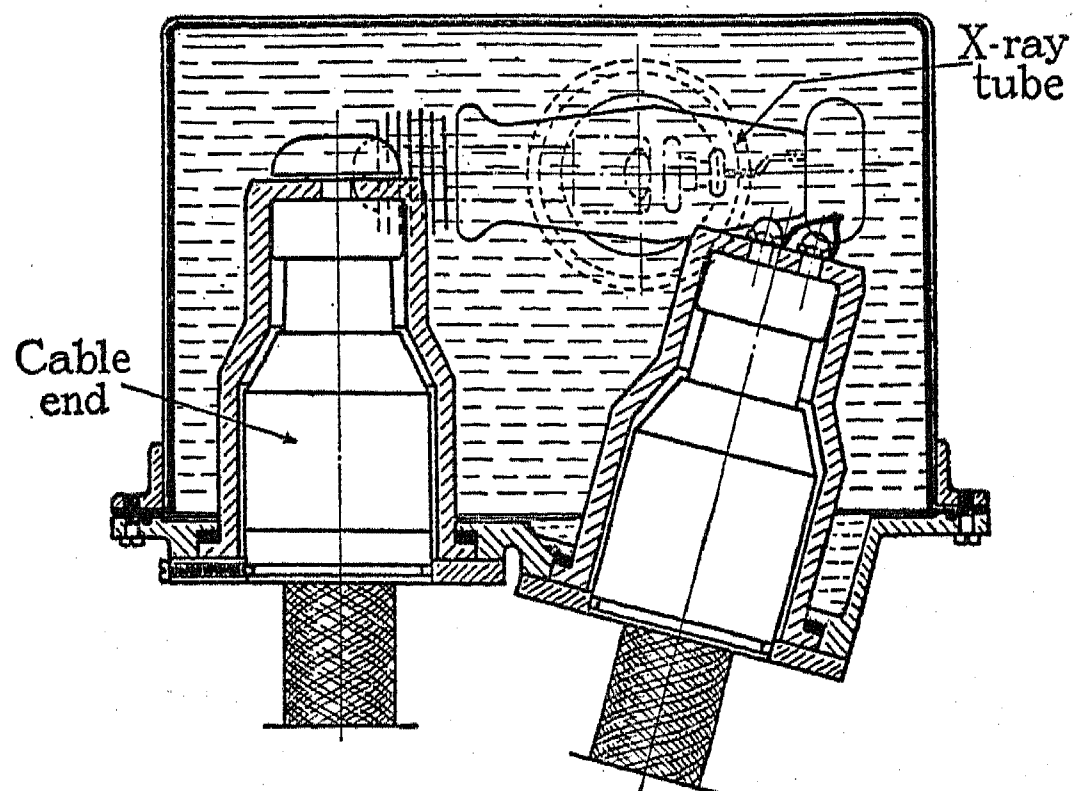


FIG. 7.—X-ray tube, oil-immersed in earthed vessel fitted with earth-sheathed cables.

there is no electrical danger when the cables are not coupled up.

A more recent higher-voltage development of this equipment comprises an earth-sheathed Metalix tube for 200 kV(P), coupled by earth-sheathed cables to a generator assembled in a rectangular earthed case. The tube, which was developed by Bouwers,† operates at 8 mA and incorporates the usual Metalix ray protection. It has forced cooling by water flowing in concentric pipes within the anode cable, while the cathode cable has twin cores for filament heating. An illustration of this tube has lately been given in the *Journal*.‡ The Villard circuit is employed in the high-voltage generator.

Some British firms make use of this type of tube in connection with electrical apparatus of their own manufacture.

A German§ arrangement of an earth-sheathed tube and high-voltage flexible cables is shown in Fig. 6. In this case the tube is housed in a container comprising two end hoods (*h*, *h'*) overlaid with lead, and a central metal portion *m*. The two hoods carry inlet sleeves into

* An X-ray tube is described as "ray-protected" when it incorporates opaque material which prevents the emergence of X-rays except through a specially provided window.

† See Reference (11).

‡ *Ibid.*, (12).

§ *Ibid.*, (13).

which the cables *c* are fixed. The cooling of the anode is effected by a stream of insulating liquid, which passes through flexible pipes *t* outside the tube casing and rigid pipes *p* inside.

In a French plant,* earth sheathing has been applied to the tube and at the same time oil immersion has been adopted for the sake of reduction of dimensions. The arrangement is shown in Fig. 7. In this case a special small tube with anode cooling radiator is used and the cables are introduced into the enclosing vessel. The dimensions of this earthed box are approximately 12 in. \times 8 in. \times 8 in., and the tube is capable of operating at 100 kV(P) and 100 mA.

In 1932 a British earth-sheathed ray-protected tube called the "Andrews Shockfree" was produced. It is a standard Andrews protected tube enclosed in a metal sheath, with oil introduced between the glass and the sheath to give adequate insulation with minimum dimensions. This tube is of remarkably small size for its rating, being 19 in. long, 5 in. maximum diameter, and designed to operate at 110 kV(P).

Ray protection is incorporated in all the earth-

tube could therefore be run close up to the animal being radiographed, and the earthing of the whole made it electrically safe.

In 1932, light metal casings for X-ray tubes to be used with cables were introduced commercially. Messrs. Philips have marketed a type of shield with cables fitted, suited to their own tubes of medium-voltage rating.

The Schall casing is an English model developed for shielding ray-protected X-ray tubes in the 100 kV(P) class. This casing accommodates British, Dutch, and American tubes.

A special instance of the application of high-voltage flexible cables to practical metallography is that of the mobile radiological laboratory,* the X-ray equipment of which was designed and constructed in the Research Department, Woolwich. This equipment, which incorporates a 250 kV(P) generator with remote control, long high-voltage flexible cables, X-ray tube and accessories, and dark room and photographic supplies, is assembled on a motor lorry, the engine of which supplies all the electrical power required. During use the electrical equipment may be enclosed, so that there is no

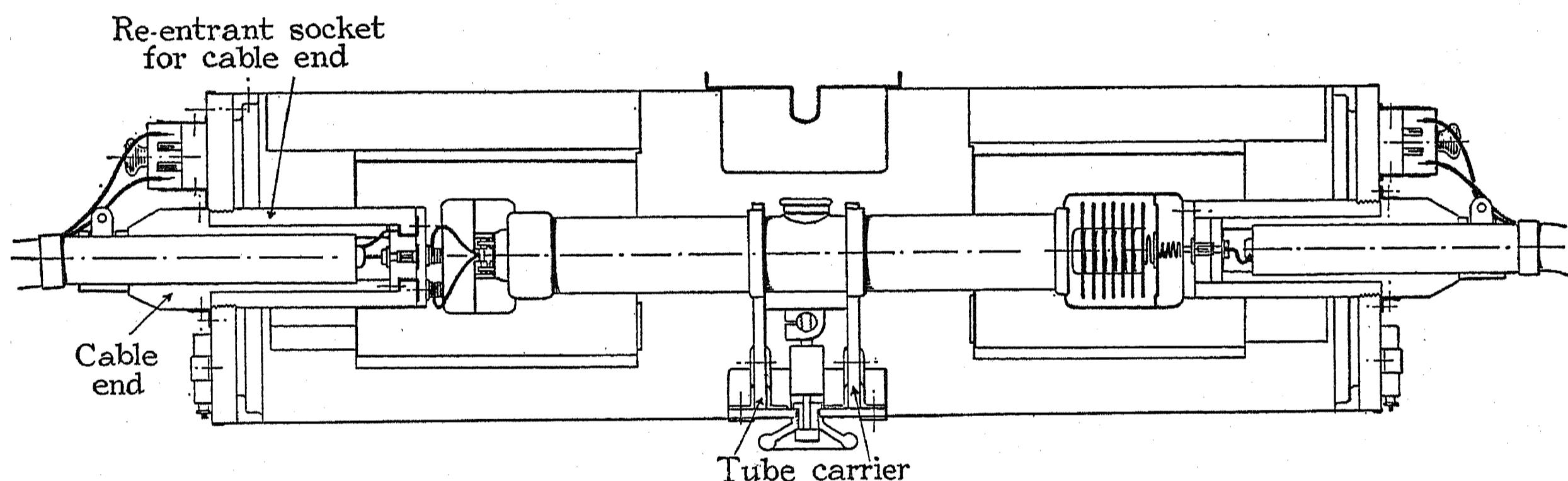


FIG. 8.—Ray-protected tube assembled in light earthed container and fitted with earth-sheathed cables.

sheathed X-ray tubes mentioned in the preceding paragraphs. A large number of X-ray tubes are still being manufactured without earthed sheathing, but very few without ray protection in some form. A ray-protected tube is generally of slender cylindrical shape, and electrical protection can easily be added by surrounding it with an independent metal casing and fitting earth-sheathed cables.

This was done to a veterinary X-ray equipment designed and constructed in 1928 in the Research Department, Woolwich. A Metalix ray-protected X-ray tube was mounted in a cylindrical metal casing at the ends of which cables were introduced for energizing the tube (see Fig. 8). The ends of the casing had hollow re-entrant insulating cylinders of smaller diameter than the casing, the enclosed inner extremities of which were permanently connected to the tube. The cable ends were made to plug in, and not until they were in position could auxiliary contacts be closed to complete the primary circuit. The tube container was mounted on a light carriage which gave a fair measure of vertical movement and could also be readily moved about the floor. The

electrical danger. In this instance the cables permit the use of the X-ray tube at a distance of 30 yards from the lorry, and being earth-sheathed they provide a safe and robust transmission. The cables can trail on the ground or be taken through windows.

Important Safety Features.

It is difficult to isolate for recommendation, devices employed to secure safety in the various equipments now available, since these devices depend on the characteristics of the particular type of plant in which they are found. Also the duty to which the plant will be put, the space available for installation, and the cost, all have a definite bearing on the choice of apparatus. Important safety features to be looked for, however, are:—

(1) (a) Earth sheathing of all high-voltage parts, and interlocking devices so arranged that when the continuity of the sheathing is broken (e.g. at the points of fixture of high-voltage cables) the supply circuit also is broken. (b) Where complete earth sheathing is not employed, suitable guards should be interposed between

* See Reference (14).

* See Reference (15).

the high-voltage parts and the operator and patient so as to make it difficult to establish human contact with the high-voltage system.

(2) Good earthing.

(3) Soundly designed control gear, making accidental closure of primary circuits impossible; and a double-pole circuit breaker.

(4) High-quality primary insulation.

(5) Correctly-fused primary circuits.

(6) If high-voltage parts are exposed in an operating room, adequate ventilation should be provided.

HIGH-VOLTAGE CABLES FOR X-RAY PURPOSES.

Cable Characteristics.

The use of flexible earth-sheathed connections between the X-ray tube and the high-voltage generator has only been made possible by the help of cable engineers, who have developed for this rather special work a type of cable designed on different lines from those common in power engineering. A number of applications of high-voltage cables to X-ray work have been mentioned. High-voltage cables of the more rigid type have been considered as a possible means of supplying X-ray rooms from remote X-ray generators by forming a system of high-voltage mains with voltage available at two or three standard values. Under these conditions interlocking high-voltage switches would be necessary, making it impossible to apply an incorrect voltage to any particular X-ray tube, and also to have dangerous access to a tube when energized.

The general requirements for an X-ray cable, however, were that it should be as small, light, and flexible as possible, should have twin cores in the case of a cable supplying filament current, and an outer sheath which could be earthed. Provision had also to be made in special cases for the cable to carry within its core the anode cooling liquid (go and return).

The idea of enclosing in an earthed sheath of, say, $1\frac{3}{4}$ in. diameter, a flexible cable the core of which was insulated from earth for a constant potential of 100 kV(P), or 70 kV (r.m.s.), was a revolutionary one to many engineers. The idea has become an accomplished fact, and indeed tests at double this voltage have been made on a rubber-insulated cable of this size with satisfactory results. For lower-voltage requirements smaller cables have been successfully employed, as, for instance, in the Metalix Junior and those cases where earth-shielded X-ray tubes are used.

The fact that very low currents are carried by these cables (generally less than 10 mA continuously and 1 000 mA instantaneously) makes the problem of their design independent of conductor heating. Dielectric heating remains, but in the case of constant potential this is almost negligible.

Oil-Filled Cable.

The necessity for flexibility at once indicates the use of rubber, although in power cables for high voltages rubber has fallen into disuse. An alternative to rubber is offered by the oil-filled cable of the Pirelli type, and although this is an attractive proposition from the point of view of size it is subject to certain disadvantages.

The ordinary oil-filled single-core cable may comprise a helical steel core surrounded by the conductor, over which is laid up the main insulation in the form of paper tape. Over this insulation is placed a protective wrapping, and then the lead covering. After vacuum drying has been carried out, oil is introduced into the helix under pressure and impregnates the insulation. The cable ends are hermetically sealed, and expansion chambers are provided to take up differences in oil volume caused by variations in temperature due to changes in external atmospheric conditions and in the load.

For X-ray purposes the comparative rigidity of paper insulation could be avoided by the use of cambric, while the disadvantages of lead from the same point of view would require its replacement by a flexible metal sheathing. Although the resistance of the central helix would not prevent its use as a conductor, the coils would no doubt act as a small choke. At one end the cable could be introduced into the transformer tank and be properly sealed, so that expansions and contractions would be provided for there. Alternatively a reservoir of size governed by the size of cable and the temperature limits could be incorporated in the central space within a winding drum.

It has been stated that a cable for a unidirectional voltage of 100 kV(P) between conductor and sheath could be made on this plan, which would not exceed 1 in. diameter. This is, of course, small, and if suitable terminals could be fitted and freedom from oil leaks maintained such an installation would be satisfactory. The excellent insulating properties of clean dry oil, the exclusion of air and moisture, and the maintenance of pressure and of complete impregnation of the solid insulation for various conditions of loading and location, are all valuable features in connection with good performance of high-voltage cable.

Some preliminary investigations of the possibilities of oil-filled cables in the X-ray sphere were made in 1929 by the Director of Radiological Research, Woolwich Arsenal, but owing to the contemporary success with rubber cables the work was discontinued.

Rubber-Insulated Cable.

Returning to the subject of rubber cables, these have in a short time reached a high state of development and will no doubt continue to be improved as the conditions under which they are used become better understood. The continued co-operation of cable designers with X-ray engineers is necessary for progress, and indeed it will be a matter for satisfaction if the points raised in this paper prompt comments from cable experts.

Unless special interior construction, such as would be suitable for passing cooling liquid, is adopted, X-ray cables are conveniently made up with twin cores so that they may be connected either to the anode or to the cathode of the X-ray tube. In the former case the two cores may be connected in parallel. The insulation between the two cores, which are generally concentric, is required to withstand operating voltages of the order of 12 volts. In practice the insulation between the cores will withstand some thousands of volts, but this is more a question of mechanical convenience than of electrical necessity.

It is not such a simple matter as it may first appear to ensure that the two cores are concentric throughout their length. The curing and sheathing processes which follow the laying-up of the main insulation around the central cores may give rise to uneven expansions and contractions, which will result in kinking and ultimately in puncture of the inter-core insulation unless special precautions are taken. Fig. 9 shows a typical kink at which puncture of the inter-core insulation had occurred in some early cable of Continental manufacture examined in the Research Department, Woolwich. Faults of this character occurred every few feet along the entire length of the cable. Radiological examination is of the utmost value in detecting irregularities of this sort, as well as

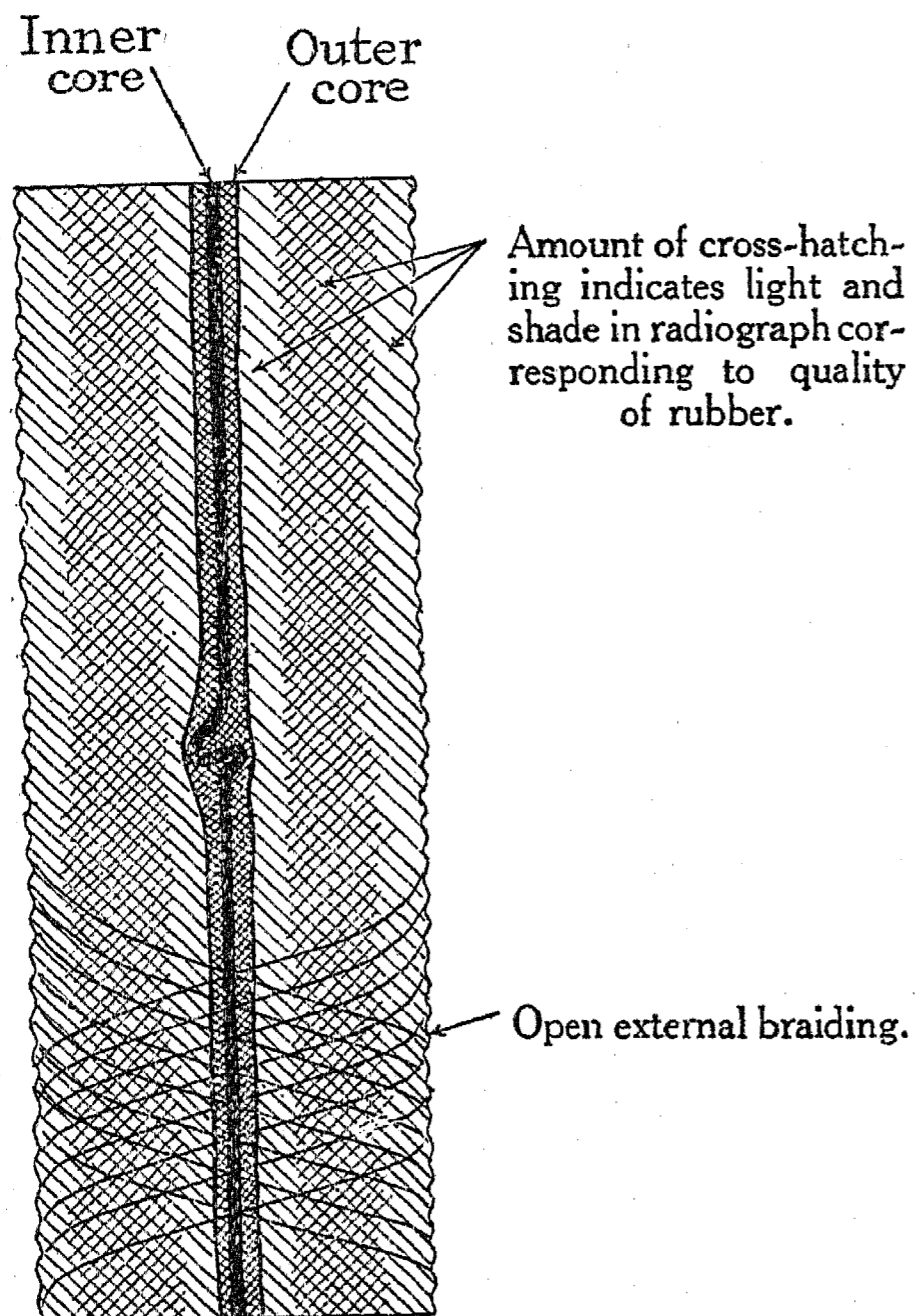


FIG. 9.—Sketch from radiograph of twin-core rubber-insulated metal-sheathed cable, showing kink in inner core at which short-circuit occurred.

the presence of air pockets arising from incomplete adhesion between the outer core and its main insulation to earth. All X-ray cables received in the Research Department are radiographed before use.

The question of what diameter, on the basis of the materials now available, is required in a cable for 100, 200, or 300 kV(P), is as yet not finally answered. Naturally the smaller the cable the better from the point of view of weight and bulk. As a rule, a cable with a sheath diameter of about 2 in. is used for unidirectional pulsating voltages of 100 kV(P) between outer core and sheath. The diameter of the outer core and the ratio of this to the sheath diameter clearly depend on the electric strength of the dielectric, the maximum permissible voltage gradient in it, and its corona-resisting properties. The value $1/e$ (where e is the base of Napierian logarithms) for the ratio of outer-core diameter to sheath diameter for the most economical section was rarely observed to hold in cables recently

examined. Three examples of the ratio for twin-core cables are $1/7.4$, $1/4.66$, and $1/2.95$.

The flexibility of the complete cable is to some degree a function of the flexibility of the cores, and this depends on the number, size, and stranding, of the wires, and hence on the core diameter.

In some tests at Woolwich a rubber cable having a sheath diameter of $1\frac{3}{4}$ in. and an outer-core diameter of $\frac{3}{8}$ in. withstood 200 kV(P) between core and sheath (neither earthed) for 18 hours when operating on unidirectional impulses at 50 cycles per sec. from a mechanical rectifier, which picked off the middle quarter of every half-wave. This voltage had been raised in steps to the maximum value. The total time was made up of morning and afternoon periods of 3 hours each for successive whole working days, and in addition at intervals the cable was subjected to mechanical tests of coiling, uncoiling, and dragging. In handling, efforts were made to avoid coiling smaller than 15 times cable diameter. No breakdown was obtained. Another cable of the same make having a sheath diameter of 1 in. and an outer-core diameter of $\frac{1}{4}$ in. was tested under similar conditions; starting at 60 kV(P) between core and sheath, the voltage was raised by 10-kV steps to 150 kV(P). This cable was subjected to four successive 3-hour runs at each voltage and did not break down.

The examination after breakdown of experimental cables has yielded valuable information. For instance, some premature punctures of main insulation between core and sheath in a particular cable were traced to the presence of air pockets. The following are some of the desiderata: (1) Adequate wall between inner and outer cores, to withstand slight kinking which may occur during the curing, etc. (2) Avoidance of air pockets between outer core and main rubber insulation. (3) Application of layers of main rubber insulation with sufficient pressure to prevent air inclusions. (4) The inside of the main insulation, i.e. the rubber immediately in contact with the outer core, to have corona-resisting qualities. (5) The outside of the main insulation, i.e. the rubber immediately in contact with the earthed sheath, to have corona-resisting qualities. (6) A corona-resisting tape between the outside of the rubber insulation and the earth sheath.

Puncture of the main insulation does not always occur radially. The track of breakdown in a rubber cable sometimes turns out to be quite irregular, having part of its length oblique to the radial planes and part of it circumferential. This effect may be due to non-uniformity of the rubber, to imperfect curing, or to gas inclusions.

Making-off Ends of High-Voltage Earth-Sheathed Cables.

Given a satisfactory cable, the ability to use it depends upon its having suitable terminals. Simply baring back the sheath to increase its surface clearance to the core, although the first step towards making the cable end, is rarely satisfactory of itself for voltages above 50 kV(P), because an intense concentration of an electrostatic field is present at the ends of the sheath (as shown in the left-hand side of Fig. 10). The lines of force traverse the air and rubber in series, and the fact that the permittivity of rubber is about 4 while that of air is 1

means that the air will be subjected to the greater potential gradient; also the air is electrically weaker than the rubber. It will be observed that the steepest potential gradient is found near the end of the sheath, and it is of little use to increase the bared length of cable since the conditions at the sheath end do not improve much as a result.

A makeshift way of overcoming this difficulty is to immerse the end of the cable in insulating oil. This arrangement is satisfactory for temporary conditions, such as may be required in connection with makers' tests. The permittivity of oil is 2 to 2.5 (the value varies with quality and condition), so that for a given line of force

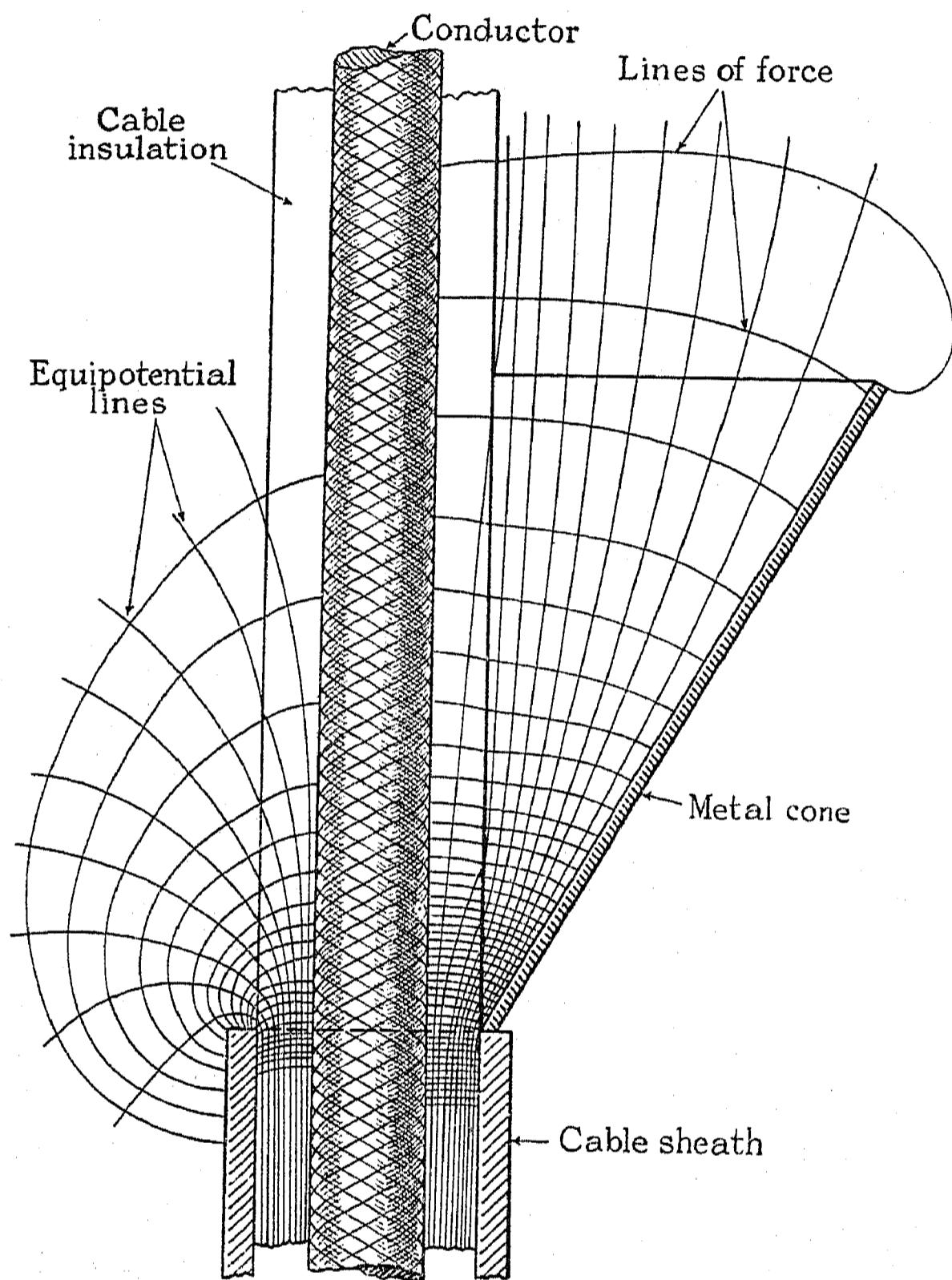


FIG. 10.—Diagram (after Beavis) showing field distribution at end of high-voltage cable.

Left. Sheath simply bared back.

Right. With metallic cone continuing the sheath.

traversing the oil and rubber from the sheath to the core the voltage gradient in the oil is a smaller proportion of the total than would be the case with identical clearances if air were present. Also, well-dried oil is electrically stronger than air, so that the advantage is twofold. An improved resistance to surface breakdown where the two dielectrics meet, a property really linked up with this twofold advantage, results from immersion in oil. Immersion of rubber in oil causes deterioration of the rubber, but protective coatings of varnish or lacquer are of assistance in preventing this. (Experiments in the rubber industry are being directed towards improving the oil-resisting properties of rubber.) Unless an oil muff of some sort be employed at the making-off point of the cable end, a suitable design has to be arrived

at for operating in air. There are two or three ways of doing this.

The method described by Beavis* for terminating an ordinary paper-insulated or rubber-insulated cable is to bare back the sheath and to surround the insulation for half the bared length with semi-conducting material. This reduces the potential gradient at the termination of the metal sheath and distributes the field more uniformly down the whole bared length.

Another method employed for relieving the stress at the termination of the metal sheath is to bare back the sheath a little more than point-to-point sparking distance for the operative voltage, and to slip an insulating sleeve over the rubber. At the point where the metal sheath terminates a bell-shaped fitting is mounted, with the open end towards the end of the cable, and a similar fitting is placed facing the first at the end of the cable. By means of this arrangement the field is distributed so that the maximum concentration is between the edges of the two bells instead of along the surface of the cable insulation.

Condenser-type cable ends have been suggested, but this solution to the problem entails the insertion during manufacture of metallic sheaths in the insulation at specified distances from the central core. The method has definite disadvantages from the manufacturer's point of view.

The intensity of the electrostatic field shown on the left of Fig. 10 may be reduced by coning the sheath away from the core, as shown on the right-hand side of the same figure. With this arrangement the sheath in effect terminates at a much greater distance from the core than it is in the length of the cable, and there is a progressive reduction of radial field as the cone widens, taking earth potential farther and farther from the core. The radiusing of the cone end (Fig. 11) reduces the intensity of the field with respect to the portion of cable which projects beyond it. An approximation to a cone by bevel and step has been used for 50 kV(P) operation in the cable-end arrangement illustrated in Fig. 8.

The air pocket in the region where the cone (Fig. 10, right) leaves the cable insulation is still highly stressed, and it is a good plan, therefore, to fill up the space between the cone and the cable with an insulating material having permittivity equal to that of the cable insulating material. The field distribution will thus be more uniform, since field refractions and disproportionate voltage gradients will be eliminated owing to the absence of the air. The filling can be tapered from the end of the metal cone to the end of the cable, and the surface length chosen for the voltage at which spark-over is required.

Ebonite, which may possess electrical characteristics very similar to those of rubber, is a convenient material to use. The resiliency of the rubber permits an excellent fit within the ebonite, and the whole can be assembled so as to avoid entrapping air in any dangerous quantity. Cable ends of this type have been made up and used in fixed and portable apparatus at Woolwich with good results. The model shown in Fig. 11 was tested with unidirectional voltage from a mechanical rectifier up to

* See Reference (16).

150 kV(P), at which value a clean spark-over occurred from sheath cone to terminal.

As solid tapered ends make rather heavy pieces in large sizes for high voltages, hollow ends have been tried and have been found to work very well. A design of this sort is shown in Fig. 12, and this model also gave a clean spark-over from sheath cone to terminal at 150 kV(P). The similar electrical performance of the two designs, which have almost identical overall dimensions, is striking. The hollow one, however, has the advantage of a bigger terminal, giving almost corona-

two terminals are required, depending on whether a cable serves the anode or the cathode end of the tube. In the case of the two there is only a very small potential difference between them, so that the problem of insulation is simple. The use of a shield (c) at the point of emergence of the cores from the rubber is effective for screening the binding wires, nuts, etc., from concentration of field. These may be accommodated in the space behind the end cap. It is advisable to coat

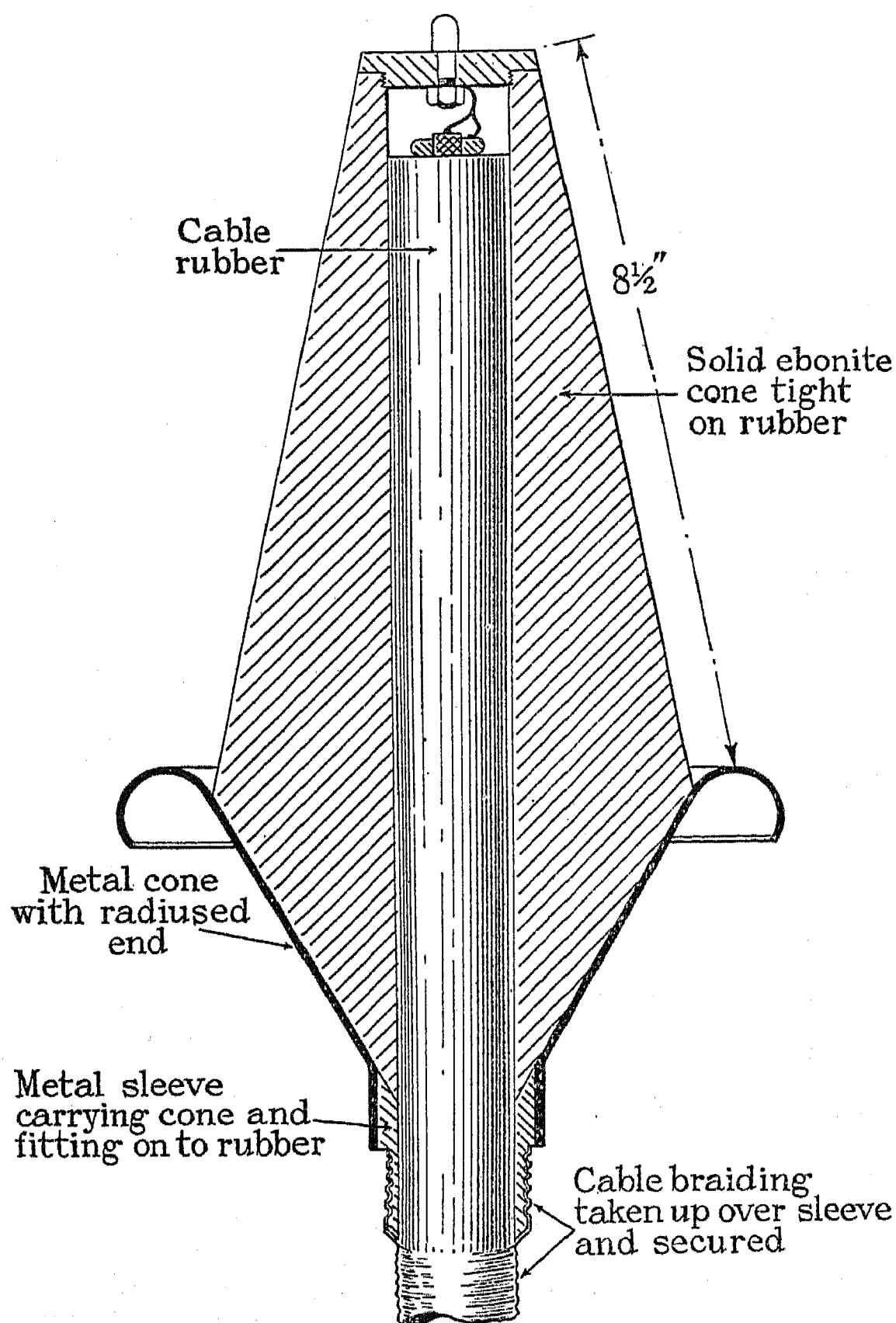


FIG. 11.—Method of making-off rubber-insulated high-voltage cable.

less operation up to spark-over. In the hollow model, although the air is not all displaced, the ebonite cable-sleeve protects the rubber from corona and the ebonite cone holds the cable and sleeve central, and protects the sleeve surface from contamination. It also tends to direct the field emerging from the end of the metal cone towards the cable end, thus reducing it in the radial direction.

A further advantage of the hollow conical cable-end is that it lends itself readily to dismantling. The model shown can be taken apart by removal of ebonite cone *a* and metal cone *b*, leaving the cylindrical portion clear. This makes winding and tying in position during transit a much simpler matter.

With reference to the question of connections for the cores of high-voltage cable for X-ray purposes, one or

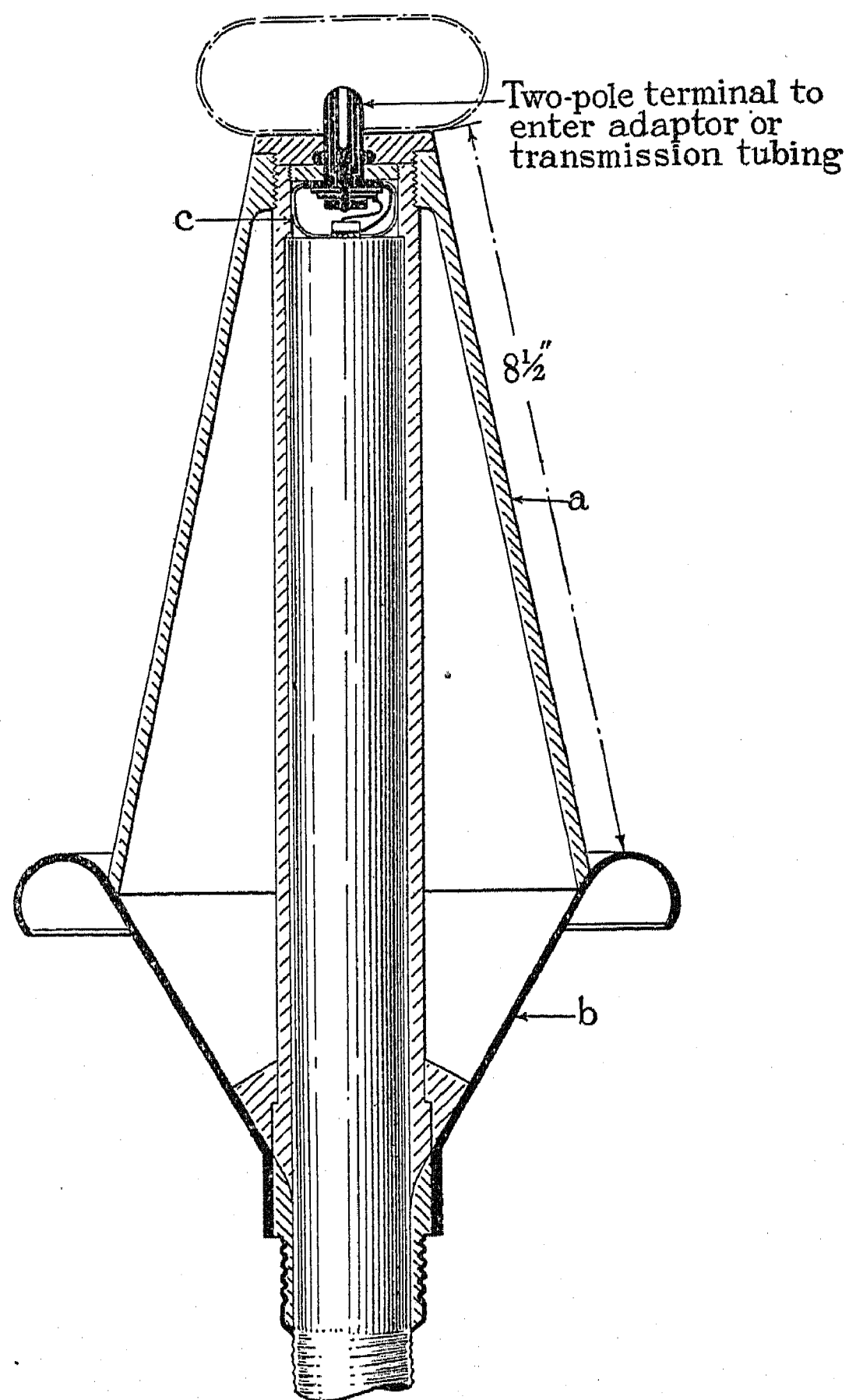


FIG. 12.—Method of making-off rubber-insulated high-voltage cable. Detachable cable end.

the radial face of the rubber with corona-resisting varnish or lacquer, so as to minimize the effects of ionized air.

The shape of the connecting end must be such as to discourage the formation of corona, and the externally-rounded fitting shown in Fig. 12 meets this requirement very well. It comprises for the cathode connection a very simple 2-pole combined plug and socket, the plug being the outer pole and the socket the inner one. When a fitting of this sort is not appropriate in particular circumstances, flexible leads can be connected to ordinary binding posts and the connections screened by an anti-corona shield (shown dotted in Fig. 12) mounted on the end of the cone. A shield of this type may conveniently house a spring-controlled rheophore for joining to the X-ray tube.

Condenser Effect of Cables.

One characteristic of high-voltage cables which may prejudice their use in long lengths for X-ray purposes is their high capacitance. The nearness of the high-voltage core to the earthed sheath, the comparatively high permittivity of the insulation (cable rubber 3.5 to 4.3, oiled condenser tissue-paper 2.3, oiled cambric 3.6), the long length, and the consequent large area of "plates," combine to form a condenser of considerable capacitance. A particular cable, for instance, which has a core of $\frac{3}{8}$ in. diameter and a sheath of $1\frac{1}{8}$ in. diameter, has a capacitance of $0.00014 \mu\text{F}$ per yard length. Supposing two 50-yard lengths of this cable were used for energizing an X-ray tube located at that distance from the high-voltage generator, the total capacitance of the cable used would be $0.014 \mu\text{F}$, and the effective capacitance across the tube would be a quarter of this, i.e. $0.0035 \mu\text{F}$, which is of the same order as the capacitance of a condenser system employed for constant-potential apparatus.

Although various kinds of rubber have different permittivities, the range of values is not great, especially for rubber suitable for this type of work. In cases where it is undesirable to have constant-potential characteristics in the high-voltage supply to an X-ray tube the effect of cable capacitance is a definite disadvantage, but it is difficult to see how cables can be used in long lengths without it. On the other hand, when constant potential is desirable the capacitance of the cables will contribute handsomely to the total condenser effect required.

Earthing of High-Voltage Cables.

Proper earthing of high-voltage cables is most important. Experiments in the Research Department, Woolwich, have shown that with cables 30 yards long, used on X-ray equipment with mechanical rectification, it is possible to get sparks to earth from the sheath at any point beyond 2 or 3 yards from where the sheath is earthed. Spark-gap measurements and oscillographic studies have demonstrated the presence of surges of over twice the normal voltage traversing the high-voltage system, especially when mechanical rectification is employed. High-frequency oscillations are also present if valve tubes are employed.

Beck* has shown by cathode-ray oscillograms that a surge due to lightning tends to raise the potential of the sheath as well as that of the conductor if the former be not earthed at the point of entry of the surge. High-frequency conditions in an X-ray apparatus approximate to those set up in a transmission line by lightning, and it is necessary to provide good sheath earthing at points of entry and reflection of surges. It is a good plan to provide at frequent (say, 4-yard) intervals, tabs connected to the metal sheath of the cable and passing through the outer fabric cover to facilitate earthing anywhere along the cable length.

Testing of X-ray Cables.

Regarding the general question of the testing of X-ray cables, it is desirable that cables be tested under conditions as near as possible to those corresponding to

actual working. In different types of plant the cables might have to operate with a potential difference between core and sheath which is alternating, unidirectional pulsating, or constant. In the case of unidirectional pulsating potentials the pulses are sometimes accompanied by considerable surging. A cable design satisfactory for a given constant voltage may break down if subjected to an alternating voltage of equal peak value.

It is difficult on the results of an ordinary works test with alternating potential at 50 cycles per sec. to forecast the behaviour of a cable installed for X-ray work. It is therefore necessary for the X-ray engineer to co-operate with the cable maker by specifying as completely as possible the duties of the cable and, unless the cable maker himself has appropriate plant, to facilitate type tests of the cable on X-ray gear.

The ratio of test voltage to operating voltage is probably best decided by the cable manufacturers until some value has been standardized.

Temporary cable-ends are used for test purposes. In each instance referred to on page 265 the sheath was bared back and the cable-ends were immersed in oil in vessels made of insulating material.

For a test the ends are sometimes supported so as to point vertically upward, and cones of cardboard, etc., are built out from the sheath to hold oil. Another alternative is the use of semi-conducting material bound round the cable and between the bared-back sheath and the core.

Some mechanical tests such as coiling, dragging over the ground, and subjecting the cable to the strain of its own weight for a specified distance between supports, are desirable before and after electrical tests. Also, since lead sheathing is not employed, X-ray examination can yield important information. Visual methods are often sufficient to reveal flaws, records of which can be preserved by means of X-ray photographs.

SAFETY REGULATIONS.

There is a Ministry of Health memorandum dated 1932 in which suggestions are made for precautions against shock from electro-medical apparatus, but this brief document has a wide scope and is not concerned with X-ray matters in particular.

With the exception of the International Regulations* which were adopted at the International Congress held in Paris in 1931, there are no regulations governing X-ray installation practice in England. The International Regulations (see Appendix) are naturally stated in general terms. Most countries have regulations of their own which deal with details. It would not be appropriate here to draw up rules, but the paper would be incomplete without some reference to foreign opinion on the subject.

The German regulations, which, the author is informed, are in close agreement with the Austrian ones, have been compiled in a very thorough manner. The German regulations for electrical safety are separate from those for X-ray protection. In connection with the former the importance of the industrial and engineering applications has been regarded as sufficient to warrant separa-

* See Reference (17).

* See Reference (18).

tion of the medical and non-medical sides of the question. An important document has therefore been prepared governing high-voltage protection in X-ray apparatus used for non-medical purposes. These rules,* which came into force on the 1st April, 1933, serve to represent the German point of view and make a very complete statement comprising two main sections dealing respectively with (a) constructional provisions, i.e. assembly, lay-out, materials, etc. (not design), and (b) service prescriptions, i.e. operating and maintenance instructions.

An important subdivision of Section (a), called "definitions," is devoted to the classification of X-ray installations into three groups: (1) those provided with earthed conductive guards, totally enveloping all high-voltage parts; (2) those where only the live parts carrying high voltages in operating rooms are thus protected; and (3) those in which high-voltage parts are provided with more or less protection, according to the manner in which the equipment is being used at any particular time. (For instance, during testing often the whole of the high-voltage system is accessible.) Another subdivision of the same section, called "stipulations," makes recommendations regarding the type of duty for which a particular apparatus is suited and the appropriate control gear according to the classification into which the apparatus falls. Thus, for example, apparatus used in shops for examination of goods on sale must comply with the requirements of Class (1). The stipulations then deal with connections with the supply, operating switches, conducting protective surfaces with or without observation windows, insulating protective surfaces, short-circuit devices for high-voltage condensers, apparatus-room door switches, light and sound signalling, and test-room arrangements.

In Section (b), instructions are devoted to the formation of safety habits among operators. Details are given regarding the use of danger notices, sequence of switching operations, protection of unused operators' positions, testing of signalling apparatus, testing of mechanical and insulating strength of high-voltage leads and supports, and the examination of protective coverings and insulating clearances.

The American recommendations† for electrical safety are incorporated as a part of a general statement prepared by the American X-Ray and Radium Protection Advisory Committee. These recommendations are divided into sections dealing with general installation, rooms for X-ray equipment, insulating high-voltage barriers, high-voltage conductors, connectors to X-ray tubes, and special requirements for anæsthetizing rooms. Although the American treatment of the subject is not so detailed as the German, all matters of major importance are included in it and only slight differences in the recommendations on certain points are discernible.

In connection with joining on to the mains the American regulations say that a plug and socket may not be used for powers beyond 6·5 kVA. If this is for constant rating it is a high figure for X-ray apparatus, and one rarely reached in practice.

It is commonly recommended that main fuses be light,

* See Reference (5).

† *Ibid.* (19).

and that if a foot switch be used it should be in series with another switch and incapable of accidental closure. The American recommendations lay down that, when used in anæsthetizing rooms, foot switches should be enclosed in vapour-proof containers. Another point made in the American regulations is that if a high-voltage switch be used it shall be so constructed that only one set of apparatus can be connected at a time. In common with the German rules details are also given regarding regular testing of the mechanical strength of supports for high-voltage parts, and checking of electrical clearances and insulating strength.

It is understood that the French authorities are preparing, for domestic use, rules which amplify the International Recommendations.

Slight differences of opinion are observed in the regulations of a number of countries in connection with the distance above the floor at which bare unprotected high-voltage cables may be supported. The German regulations, for instance, according to Wintz* suggest a minimum of 2·2 metres, 2·3 metres for 75–130 kV(P), and 2·5 metres for 130–250 kV(P). The Czechoslovak regulations give instructions in terms of a formula in which the kilovoltage is the independent variable. This formula yields approximately the same values for the necessary clearances. The plan of varying clearances with voltage leaves matters a little indefinite should a set be used generally at a lower voltage than its maximum. If the high-voltage leads are arranged according to standards for this lower voltage, and the set be suddenly required to operate at its maximum and the necessity for increasing the clearances be overlooked, a serious hazard appears. The recommendation for a clearance not less than 9 feet (3 metres) by the International Congress appears to be superior.

Immediate access to information regarding first aid in cases of electrical accidents should be available, and it is advisable for the X-ray personnel to be trained in the administration of this emergency service.

The need for detailed instructions to promote safety from electrical dangers is a real one, and it is suggested that the Institution, in co-operation with the British Institute of Radiology, might set up a body to deal with the matter at no distant date.

The author's thanks are due to the Director of Artillery for permission to publish this paper, and to the firms named in it for much helpful information. It is a pleasure to acknowledge the kind interest and helpful criticism of Dr. V. E. Pullin, C.B.E., Director of Radiological Research, Royal Arsenal, Woolwich, in connection with the preparation of the paper, and also the assistance of Mr. D. E. Barnes, B.Sc., in experimental work.

APPENDIX.

ELECTRICAL PRECAUTIONS IN X-RAY ROOMS.†

The floor covering of the (medical) X-ray room should be of insulating material, such as wood, rubber, or linoleum.

Permanent overhead conductors should not be less

* See Reference (1).

† Section 4 of the International Recommendations for X-Ray and Radium Protection, revised Paris, July, 1931.

than 9 ft. (3 metres) from the floor. They should consist of stout metal tubing or other corona-less type of conductor. The associated connecting leads should be of corona-less wire kept taut by suitable rheophores.

Wherever possible, earthed guards or earthed sheaths should be provided to shield the more adjacent parts of the high-tension system. The use of X-ray equipment having the high-tension circuit completely enclosed in earthed conductors is specially recommended. Unless there are reasons to the contrary, metal parts of the apparatus and room should be efficiently earthed.

The use of quick-acting double-pole circuit breakers is recommended. Over-powered fuses should not be used. If more than one apparatus is operated from a common generator, suitable overhead multi-way switches should be provided.

Some suitable form of kilovoltmeter should be provided to afford a measure of the voltage operating the X-ray tube.

Special electrical precautions should be taken in rooms where anæsthetics are used in conjunction with X-rays.

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DISCUSSION BEFORE THE INSTITUTION, 22ND FEBRUARY, 1934.

Dr. V. E. Pullin: The subject of this paper is of very great importance, particularly as X-rays are becoming more generally used not only in medicine but also in a variety of branches of industry. Confidence in the safety of X-rays among such prospective users is not very general, and it is therefore all to the good that we should have available such reassuring information as is given in the paper. At Woolwich we are chiefly concerned not with the medical but with the industrial and engineering applications of radiology, and so we have to legislate for untrained personnel. We therefore have to make our apparatus and technique as foolproof as possible. X-ray apparatus makers have achieved such a high standard of design and manufacture that X-ray equipment nowadays gives complete protection from electric shock, and to my mind this is even more important than protection from X-rays. One of the greatest difficulties which we have met with in the

development of the use of X-rays in engineering inspection problems has been that of transporting cumbersome, heavy specimens to the radiological laboratory. We could not move our equipment to the specimens because of the clearances demanded on account of the high voltage involved. The development of high-voltage earth-sheathed cables, however, has enabled us to take our equipment into a factory or machine shop and investigate heavy and expensive forgings even while they are still on the lathe, if that is desirable. We are also able to take our X-ray tube from a lorry through a crowded factory or shop without endangering the personnel. I have therefore always regarded the development of these cables as a very important branch of our research work. It is gratifying to find that, contrary to expectations, the voltage-drop due to the use of long lengths of these cables is not great.

Dr. G. W. C. Kaye: My interest in X-ray electrical

protection dates from about 1917, when during the War I held the position of Chief Inspector of Materials at the Air Ministry. There had been a number of complaints concerning the breakdown of high-tension cable. We therefore set up a portable X-ray outfit and on examining lengths of these cables we found that most of the trouble was due to the kinking of the wire inside. We had to design a shockproof outfit, because it had to be put in the hands of people who did not know much about X-rays. I do not agree with the author that there are no British safety regulations governing X-ray installation practice. As Secretary of the International X-ray and Radium Protection Committee I may perhaps be allowed to say that it was entirely due to the efforts of this country that the International Recommendations ever came into force. British recommendations on the subject were drawn up as long ago as July, 1921, by the British X-ray and Radium Protection Committee, which was composed of representatives of various public bodies, including the Institute of Physics, the Royal Society of Medicine, the Radium Institute, the Röntgen Society, and the National Physical Laboratory. These recommendations were drafted at very short notice, in view of a series of casualties to X-ray workers. The recommendations have had a profound influence on the safety and well-being of the X-ray worker in this country, both from the point of view of ray protection, which was the stimulating cause, and from that of electrical protection and ventilation. In the early days the X-ray worker was almost always given underground accommodation, sometimes without windows and often damp; it was usually an inaccessible room which nobody else wanted. The modern X-ray department, on the other hand, is light, airy, spacious, and well adapted for its purpose. The 1921 Recommendations dealt with insulating floors, corona-less overhead tubing, the dangers of slack high-tension wires, the significance of earthing, the value of double-pole switches, the need for accessible double-pole switches which do not tend to close automatically, the dangers of multiple high-tension connections, and the importance of ventilation. Two years later the recommendations were revised, and such points as the minimum height of conductors from the floor, and the advantages of quick-acting circuit-breakers and kilovoltmeters, were dealt with. A further revision took place in 1927, when various other points were added, such as the importance of having a discharging device when using condenser generators. The following year the British Committee took a notable step. At the Second International Congress of Radiology, held in Stockholm in 1928, where some 30 nations were represented, the Committee put forward recommendations based very closely on, but not so detailed as, the British model; and, with trifling modifications, these were adopted. The British X-ray industry had from the first supported the work of the British Committee, and at the international exhibition of apparatus held at Stockholm the British manufacturers showed safety devices which created a profound impression, and indeed resulted in modifying design for the rest of the world. Details of ventilation, sizes of rooms, and the danger of promiscuous earthing, were brought up for the first time in 1928. After the Stockholm Conference a number of

other nations drew up national regulations of their own, largely based on the International Recommendations; among them were Germany, the United States, Austria, Denmark, Greece, Hungary, Russia, Sweden, Spain, Switzerland, and Holland. The League of Nations also took up the subject and issued a very comprehensive booklet. The American Committee followed the plan of the British Committee; they sought the assistance of the Bureau of Standards, which collaborated with them in much the same way as the National Physical Laboratory has collaborated with the British Committee. During the last 13 years, several hundred X-ray departments and installations have been inspected and reported on by the National Physical Laboratory on the basis of the British and the International Recommendations. The author's statement that the International Regulations were adopted at the International Congress held in Paris in 1931 is not quite correct. The Regulations had already been in existence for 3 years then. Shockproof outfits were especially commended by the International Committee in 1931, and in this connection I think we ought to pay a tribute to the practical part that Dr. Bouwers of Eindhoven has played in all this work; he not only produced the first self-protective X-ray tube (based on the British recommendations) but afterwards, when the menace of high voltages became more pronounced, he evolved the shockproof type of tube and the shockproof cable. The British Recommendations are at present being revised and expanded, and I find that all the safety features mentioned by the author on pages 263 and 264 are dealt with. In conclusion, I should have liked to have seen some reference in the paper to the value of rubber mats or of rubber shoes, as a supplementary precaution in X-ray work. We have tested from time to time at the N.P.L. crepe-rubber mats $\frac{1}{4}$ in. to $\frac{1}{2}$ in. thick, and found that they will stand up to about 150 kV (r.m.s.) before puncturing. Their d.c. puncturing values are, of course, considerably higher. Walking shoes with rubber soles and heels were found to have a resistance of over 100 megohms when dry, but when they were wet this dropped to about 0.5 megohm. Similar shoes made entirely of leather gave a figure of about 2 megohms, but if the soles were nailed instead of hand-sewn the value was much lower. The best shoe appears to be the ordinary tennis shoe. Such shoes with rubber soles whether dry or wet were found to have a resistance of over 100 megohms. It is not, of course, suggested that if rubber mats or shoes are used one should relax the standard electrical precautions to which reference has already been made.

Dr. W. V. Mayneord: In medical practice the induction coil is disappearing, and the constant high-potential plant is taking its place, doubtless with consequent increase of danger. On the other hand, in medical plants the possibilities of complete enclosure are perhaps greater, as the plant does not have to be moved. Apparatus like the Holfelder cannon, a long lead-lined cylinder, seems to be very suitable up to voltages of 200 kV. Above this voltage, at any rate up to 400 kV, that type of apparatus shows considerable promise. With regard to the question of mobility, as far as medical practice is concerned it is sufficient if the tube can be raised and lowered and completely rotated on its axis.

This simplifies the problem considerably. As regards high-tension cables, one problem associated with them is their weight. The X-ray tube is normally rather a fragile piece of apparatus, and occasionally difficulty arises on account of the weight of the cables associated with it. I should like to raise the question of whether the mid-point of the windings of the secondary transformer should or should not be earthed. Clearly if it is the current flowing through a person which matters, then whether or not this point is earthed is of great importance. I should like to have the author's views on this question. Very great advances in X-ray apparatus have been made recently. For instance, a complete radiography plant was exhibited by Dr. Bouwers in London last December in which the whole apparatus, including the X-ray tube, transformer, and switchgear, for voltages up to about 50 kV, was of about the size of an ordinary hand camera.

Dr. Bernard Leggett: The Institution can render valuable service in discussing the manufacture of X-ray apparatus from the technical aspect. The paper largely deals with the question of protection, and in this respect the developments of the past few years, unfortunately chiefly foreign, are well reviewed. On page 253 the author unwittingly solves the whole problem of X-ray protection, in his phrase "have enabled X-ray apparatus to be placed with confidence—from a safety point of view—in skilled hands." I should like to ask, why should X-ray apparatus be put in unskilled hands? In the medical applications it is such unskilled use, whether by laymen, or by untrained and inexperienced medical men, which gives rise to serious errors, so bringing medical radiology into disrepute and preventing the more extended use of the most important method of medical and surgical diagnosis in existence. My experience of industrial, as distinct from medical, radiology, is largely secondhand, but the same considerations no doubt apply. If industrial radiology is to be carried out as the author states, by those who are little more than advanced labourers, then its future is not promising. One particularly regrets to find that in a Government establishment such as the Royal Arsenal, which is not subjected to such strict economic conditions as a commercial establishment, this work is being deputed to unskilled workers. Such men cannot possibly have as much responsibility as a skilled operator, who, owing to his knowledge, does not require the same degree of protection. The author mentions the inspection of shell fuses by X-rays: I would point out that accurate fuses are far more likely to be obtained by paying a pound or so a week extra for the services of an intelligent and educated operator. The additional cost, spread over expensive manufactures such as fuses, is negligible, and accurate fuses, in actual warfare, may determine the life of many soldiers. In the realm of medical work for therapeutic purposes, particularly in the treatment of diseases of the skin, results are only obtained by giving maximum dosage, which demands knowledge and skill. A recent American editorial* refers to the principle that, in medical radiology, thorough medical training is necessary, but points out that physicians should not engage in industrial work. I would commend it to the present author's notice, as the U.S.A. writer states: "It would

seem an obvious parallel of the first paragraph (which stipulates that medical radiology should be carried out by medical men and not laymen) that such inspection service can be best given by a broadly trained engineer specializing in radiology. To do intelligent radiography of materials one might need as deep an insight into their structure and use as one needs of anatomy and physiology to do intelligent radiography of man." In English radiological literature generally, as in the present paper, the question of protection takes major importance; whereas in foreign literature this subject is regarded as only of minor importance. Dr. Kaye is, I think, incorrect when he attributes the origin of protective recommendations (which, very fortunately, are not regulations) to this country. This point is dealt with on page 334 of "The Science of Radiology," recently published jointly by the U.S.A. radiological societies, and apparently the U.S.A. were first in this field.

Mr. C. Morgan Davies: Now that earth-shielded insulation is standard, danger of shock from the high-tension system will be avoided in the case of equipments installed in the future. Unprotected equipments having centre-tapped and earthed secondary systems are, however, common, and as serious shocks may be obtained from this type of apparatus it is desirable to fit such equipments with earth-shielded tubes and cables. I cannot see why the author should consider the peak voltage when calculating the shock current to earth. It is stated that the maximum current one can receive from the centre-tapped transformer under consideration is $5 \times 10^4 / 10^6$ amp. = 50 mA, whereas, considering the inertia attributed to the muscles, $5 \times 0.707 \times 10^4 / 10^6$ amp. = 35 mA would appear more correct. The difference may be considerable under certain shock conditions. In hospitals we are obliged to use the type of copper strip recommended by the author for earthing the various pieces of apparatus in X-ray rooms. Usually, existing floors have to be dealt with, the strip being laid under the rubber carpet. The $\frac{1}{8}$ in. \times 1 in. section recommended appears unnecessarily heavy, cumbersome, and expensive; $\frac{1}{16}$ in. \times $\frac{3}{4}$ in. section has been found satisfactory for hospital work. It is often difficult to obtain a satisfactory earth connection from a water pipe or outside source, and provided the metallic envelope of the supply cable is earthed (as it should be) it would seem better to bond to this than to anything else. In this connection, if we applied and satisfied the requirements of I.E.E. Wiring Regulation No. 127 (B), which refers to the resistance of earthing circuits, should we not be assured of safety? Transforming equipments serving several pieces of examination equipment and having complete earth-sheathed high-tension systems must include a number of permanently-fixed cables. Here all sheaths of outgoing distributors should be bonded to the earthed tank of the oil-immersed selector switch, continuity being obtained through the junction boxes joining fixed cables to flexibles and via tube shields and examination apparatus to the copper strips already referred to. In this way every branch would be efficiently earthed at both ends. Would the author recommend in addition to this the provision of earthing tabs at frequent intervals along the cables? For this type of installation the oil-filled cable appears to offer many

* *Radiology*, 1934, vol. 22, p. 247.

advantages, such as reduced diameter and capacitance, and absence of rubber in contact with oil. The oil immersion of rubber-insulated tails, protected only with a coat of varnish, leaves doubt concerning the permanent effectiveness of this method of protecting the rubber insulation. Presumably the capacitance of long lengths of sheathed cable is unimportant where lengthy periods of radiographic exposure are permissible. This factor needs careful consideration where very short exposures, such as those required for chest radiography, are desirable; the type of rectification employed and the capacity of the transforming equipment to deliver high initial charging currents have a marked influence in these cases. Incidentally, where long lengths are installed, if the cross-sectional area of conductors carrying cathode heating current is inadequate and the inherent voltage regulation of the filament transformer is poor, the resultant voltage-drop together with possible variations will contribute towards instability of the apparatus.

Mr. G. E. Bell: I should like to make a few comments on the general problem of the earthing of X-ray equipment from the point of view of safety. The question of earthing the transformer itself has already been raised in the discussion. The German safety regulations state definitely that no part of the high-voltage system of non-shockproof equipment is to be earthed. The principle underlying this regulation is that it is unlikely that a person will establish contact with both high-tension contactors, and, if he establishes contact with only one of them, the path of the current is the high-resistance circuit through the body and then to earth via the floor and the insulation of the transformer. With regard to the overhead distribution system, little can be done other than to carry it 9 ft. high to as great an extent as possible. There are one or two places where the high-tension distribution system must come near the operator, the most usual point in ordinary hospital equipment being the leads associated with an X-ray tube used in the over-couch position. This is the most vulnerable part of the whole equipment. Associated with the high-tension generator we have the control table, and the author has introduced the controversy as to whether this should be earthed. It seems to me that where there is any risk of contact with the high-tension conductors (this particularly applies to the over-couch tube) it is better to have all the ancillary apparatus insulated. According to the International Recommendations the floor itself should be insulated, but a person standing on an insulated floor might make contact with a couch or a screening stand which itself was satisfactorily earthed, and thus nullify the effect of the insulated floor. In certain cases, particularly where the tubes are used in the under-couch position, it is very simple to make the whole system shockproof, even when using the conventional type of apparatus. In many hospitals the same couch is used for both over-couch and under-couch work, and it would therefore appear that the advantage lies in making the couch of wood or similar insulating material and providing properly-insulated controls. If the equipment is of such a character that it is impossible to touch the high-tension leads, everything should be completely earthed, including the control table, because there is some danger of

the latter becoming live at the mains voltage. The author implies that it may be desirable to lay down some definite rules for ensuring safety. I doubt whether this could be done at the moment, in view of the diversity of apparatus in existence. I think it would be better to lay down guiding principles such as are contained in the International Recommendations, which might with advantage be amplified to some extent. While I agree that a constant-voltage generator is inherently more dangerous than a transformer generator, I would point out that this is not the universal opinion. The constant-voltage generator shares with the induction coil the property of bad regulation, and in the event of a partial short-circuit its terminal voltage collapses markedly. Dr. Wintz, in his League of Nations pamphlet on the subject, lays it down as his opinion that a constant-voltage set is not as dangerous as a straightforward transformer set.

Mr. A. Beetlestone: The paper contains no guidance as to the future trend of design, particularly with regard to high voltages for medical work. The types of apparatus which the author discusses are quite satisfactory for voltages up to 200 kV, and since the majority of sets have the mid-point earthed they have only to be insulated for 100 kV. The question of ray protection becomes acute, however, for tubes insulated for more than 100 kV. All tubes for deep-therapy treatment ought to be enclosed in ray-proof containers, which for preference should consist of earthed lead shields. For tubes operating at ± 100 kV to earth the dimensions indicated by the author are reasonable and the lead screen is not too heavy; but in tubes operating at 400 kV the diameter and length of the shield and screen are approximately 4 times as great, while the thickness of the lead required increases from 5 to 25 mm. Its weight is therefore multiplied 20 times. The author makes no detailed reference to ray protection; although this is a subject which should rather be dealt with by the Institute of Radiology, it cannot be neglected in considering the electrical aspect of precautions for tubes operating at higher voltages than those referred to in the paper. The present methods of protecting tubes will become impracticable with increasing voltages. As an indication of the possible trend of future practice I would mention that the Metropolitan-Vickers Electrical Co. have developed an X-ray tube which does not suffer from the inherent disadvantages of the sealed-off type. It is continuously evacuated, and constructed of steel and porcelain. The porcelain is of the high quality used for porcelain line-insulators, and the rest of the tube is made of solid-drawn steel tube. The diameter of the steel envelope at the anode end is only 8 in., which makes it possible to put any desired thickness of lead round it. The tube can be mounted on a worm lifting gear, by which it can be moved up and down through any given distance. The couch can be placed above, below, or at the side of the tube. This type of equipment would seem to offer considerable possibilities for the future, in the direction of high voltage and high powers. I do not agree with the author as to the advantage of using low-voltage control circuits. Fatal accidents have been caused by very low-voltage circuits, and even if the control voltage were reduced to 20 volts, at a consider-

able increase in cost, one could not guarantee perfect safety. With regard to the protective circuit mentioned on page 255, we have always used a resistance leak of the order of 200 000 ohms across the condensers to get rid of electrostatic trouble. I agree entirely with the author's remarks on the use of signal lamps. One point which he does not mention concerns high-voltage sets employing condensers. The condenser may in certain circumstances remain charged even though the circuit is dead; and this drawback has been overcome in the Metropolitan-Vickers plant by the provision of an automatic condenser short-circuiting switch which, being spring-loaded, closes when the current is shut off. Auxiliary switches are provided which operate lamps in the illuminated diagram. In my opinion the time is not yet ripe for the adoption of a definite safety code. Developments are taking place very rapidly, and any such code would have to accommodate progress in the design of deep-therapy apparatus. With regard to relay protection, the overload high-voltage relay provided in the Metropolitan-Vickers equipment will trip out the high-voltage circuit in $\frac{1}{50}$ sec. In conclusion, I should like to mention that the Metropolitan-Vickers Co. are indebted to the author for material assistance in the improvement of the Miller coil.

Mr. F. C. Raphael: I want to join issue with Dr. Kaye and Mr. Bell, whose remarks about insulation seem to me to be in direct contradiction to the International Recommendations. These Recommendations require earthed guards for the more adjacent parts of the high-tension system, and efficient earthing of all metal parts of the apparatus and room. Mr. Bell, on the other hand, recommends insulation of all controls, and Dr. Kaye has been making experiments with insulated mats and goloshes. There is an old proverb "once bitten, twice shy." The converse to this, "once unhurt, twice foolhardy," would have particular application in the matters we are considering. If we adopt Dr. Kaye's suggestion, an unskilled operator wearing goloshes and standing on a rubber mat may touch a high-tension conductor or a 400-volt conductor harmlessly. Having done so thinking there is no danger, he will do it again and again, until he eventually touches the earthed part of the couch at the same time and sustains a severe and possibly fatal shock. Do not let us, therefore, preach earthing and insulation simultaneously, because if we do we shall get into difficulties. We have had this experience in electric lighting work, and we do not want to go through it again with X-ray work. My ideal arrangement for X-ray diagnostic rooms would be a large earthed metal tube projecting from the wall, to contain the X-ray tube or tubes, and with three windows—one at the end, one at the top, and one at the bottom. The apparatus would be in another room behind this wall, and be actuated by remote-control switches. Suitable mechanical arrangements would be provided for adjusting the position of the patient relatively to the tube. Unfortunately, medical opinion has decided otherwise; the doctors insist that the patient and the tube must both be adjustable with extreme accuracy. This is one reason why shockproof apparatus has been so slow in gaining ground in hospital practice. We insist wherever we can on

shockproof apparatus for over-couch work, because the old-fashioned arrangement is so dangerous, but for ease of adjustment additional tubes are then requisitioned for under-couch, screening stand, and sinus stand, and the cost becomes prohibitive except for a large hospital. If we have to move the tube and not the patient, the ideal arrangement is the self-contained Victor apparatus which was illustrated in one of the author's slides; unfortunately, however, most doctors have agreed that this has not sufficient power output for all purposes. Until quite recently a 25-kVA transformer with 4-valve rectification was favoured, but obviously this equipment is too heavy to be mounted on a universal joint. I think we should try to encourage the transformer makers to devote more attention to the question of ratings and design. The 25-kVA transformer only requires its full output for a small fraction of a second, and for the rest of the time a much lower output is required. If the matter were gone into thoroughly by the transformer experts, a much lighter and smaller transformer could no doubt be produced. In the opposite direction we have the fan-cooled "Rotalix" tube, which again demands bigger outputs. For general routine work a simpler apparatus is, however, required. It would also be advisable to arrive at a standard routine, so as to avoid every doctor employing a different method. Turning to the question of ventilation, I should like to know what is the idea of having 10 air-changes per hour in the X-ray room. I should also like to ask about the automatic cut-off relay, which apparently has a time element. Does this operate in time to prevent a fatal shock? If the author would tell us a little more about his experiments on the breaking-down of cables it would be of interest. If a cable breaks down near the tube end, we have to get rid of the 50 000 volts between the shield and the earth plate; even taking into account the fall of potential over the spark-gap, there will be a distinct potential gradient down the sheathing of the cable. I should like to know the magnitude of this potential gradient. We must bear in mind that a rubber cable of this sort will not last for ever; it will eventually break down as the result of secular changes in the rubber itself. When this happens, can we rely on the resultant discharge being of such high frequency that it will do no damage, or on practically the whole of the potential drop disappearing in the spark-over? I agree with the author's remarks with regard to tapplings on transformers. Many operators are not satisfied with 6 tapplings. If we are permitted to take a voltage of 400 volts from one phase of our 3-phase system, we can lead this directly to the step-up transformer, have 6 tapplings worked by contactors, and bring a low-voltage supply from a double-wound transformer to our switch table to work the contactors. We are then absolutely safe on the medium-voltage side. As to signal lamps, I am up against the same difficulty as the author. Lamps may be removed, or the doctors may order the contractors to put a switch in the circuit so as to enable them to switch them off. In practice it is difficult to find positions for these lamps, for any light whatsoever is objected to when screening. On shockproof gear I am inclined to omit the warning lamps, with the possible exception of a lamp to show that the main switch is on. I favour the fitting of

warning lamps outside the X-ray room, however, because it is a safeguard against the risk of people entering the room suddenly and so causing the occupants of the room to look round and perhaps touch a live conductor. My usual practice, therefore, has been to have a green lamp outside which lights up when the main switch is on, and a red lamp which lights up as soon as the filament transformer is in circuit, i.e. just before the high-tension supply is on.

Mr. L. G. H. Sarsfield (*in reply*): I am glad that Dr. Pullin emphasizes the importance of electrical safety in places, such as engineering shops, where people not actually engaged in radiographic work are liable to be in close proximity to the apparatus. The removal of the necessity for large electrical clearance distances and the general increase of mobility cannot fail to react favourably upon the development of X-ray work in the engineering sphere.

It is reassuring to learn from Dr. Kaye of the large part played by British authorities, including himself, in directing attention so long ago as 1917 to the importance of safety in X-ray apparatus, and to be reminded of their work on the International Protection Committee. My remarks on the absence of regulations governing installation practice in England refer not to the broad guiding principles of an international statement, but to more detailed and particular regulations (such, for instance, as the I.E.E. Regulations for the Electrical Equipment of Buildings), which indeed are lacking. The Appendix to the paper quotes the Electrical Safety section of the International Recommendations in full, and by contrast gives some extracts from foreign countries' regulations which provide definite rulings on matters of choice, lay-out, wiring, and maintenance of plant. Contrary to Mr. Bell's and Mr. Beetlestone's views, I feel that such regulations are possible at the present time and would be very helpful to consulting engineers, designers, and contractors. The character of the X-ray industry may go on changing for a number of years, but sufficient is known of general lines of manufacture to make a comprehensive document which would have real value. This, of course, could be brought up to date when necessary.

Mr. Raphael draws attention to an anomaly in the International Recommendations which advocates both insulated floors and earthed guards. Here are mingled two principles which call for some definition, for it is of little value to have an insulated floor if an earthed guard is accessible. This question is returned to in connection with remarks by other speakers.

The revision and expansion of the present British recommendations now promised will be welcome.

I agree regarding the value of rubber mats as a supplementary protection, but their use requires the complementary insulation of couch, control table, etc. Otherwise the eventuality visualized by Mr. Raphael, in which an operator standing on an insulating mat touches a high-voltage point and at the same time an earthed couch, becomes a serious one.

The weight of high-voltage cables in the 100-kV(P) (core to sheath) class is a disadvantage, but one that can be minimized by suitable supporting arrangements. Some tubes are designed so that the metal sheath takes

the strain due to the weight of the cables. Where this is not the case provision must be made to support the cables independently from the floor or on the tube stand. The design of the tube shield illustrated in the paper, with the cable emerging from the tube towards its centre, is to be commended for its distribution of weight. Dr. Mayneord's favour of the Holfelder cannon type of equipment with, I presume, the high-voltage apparatus in a room separate from the operating room, is shared by Mr. Raphael; this certainly offers a very positive solution to the safety problem. The scheme requires a separate room for the apparatus, however, whereas equipment with earthed cables effects economy of space without sacrifice of safety.

The question raised by Dr. Mayneord regarding earthing of the mid-point of the transformer is important. The advantage of earthing the middle point of the high-voltage winding, from the designer's point of view, is that the maximum potential of any part of the winding is held definitely with respect to earth. This statement holds for power frequencies: there is always a tendency for high-frequency potentials to be superimposed on main potentials in X-ray and similar oscillatory circuits. If the mid-point of the secondary winding is not normally earthed and one end becomes earthed by accidental human contact, the tendency is for the other end to increase in potential to twice its normal value. This may give rise to a discharge to earth at the core or primary, or by sparking over the secondary terminals, and the insulation will meanwhile be strained. Under these conditions the person making contact will be in a higher-resistance discharge circuit than he would be if the winding were definitely earthed, and he will suffer a less severe shock. The measure of safety depends upon the contact time and the amount of discharge current which results under these conditions.

If it is possible for an operator or patient to touch a high-voltage part of the circuit it is safer to have a non-earthed transformer.

Now the X-ray tube itself is liable at a time of unstable running to give rise to potential shift on a non-earthed transformer secondary. The windings, terminals, and insulators, are thus in danger of being over-stressed and therefore should be designed more liberally to meet this condition. This makes costs higher.

For earth-sheathed X-ray apparatus there would appear to be no disadvantages from the safety point of view in X-ray transformer mid-point earthing, and there are real advantages from the point of view of apparatus design.

Dr. Leggett asks a question in connection with my statement that safety features have enabled X-ray apparatus to be placed with confidence—from the safety point of view—into unskilled hands. The inspection of certain objects (such as shell fuses) involves ascertaining whether particular components are present and correctly disposed or are absent. When a reliable technique has been evolved for this purpose apparatus can be designed to produce, semi-automatically, X-ray pictures which are very simple to read. Moreover, the large quantities of these objects which have to be handled make their examination a matter of concise routine and constant repetition, which can be dealt with by scientifically

untrained personnel for whom foolproof technique and apparatus are necessary.

In regard to the point raised by Mr. Morgan Davies on the subject of maximum or r.m.s. value of voltage for calculating shock current, I think the former (which I have adopted) is correct since pulsating or alternating current at power frequencies is capable of giving shock, which suggests that the muscles can respond to impulses of these frequencies. The maximum value of the current during the wave is probably responsible for the large proportion of the muscular reaction. If this is so, the maximum value of the voltage should be employed in calculating it.

Since voltage surges on X-ray apparatus, particularly with mechanical rectifiers, have the characteristics—in regard to potential difference and frequency—of disturbances due to lightning, the choice of earthing ribbons has been rather influenced by lightning-protection practice. It is understood that Admiralty regulations quote 1 in. \times $\frac{1}{8}$ in. as proper dimensions for earthing ribbons used in this connection. The mechanical strength and volume of material in respect of corrosion are not the least important points. If smaller dimensions are desirable on the score of cost, I think $\frac{1}{2}$ in. \times $\frac{1}{8}$ in. would be better than $\frac{3}{4}$ in. \times $\frac{1}{16}$ in.

I do not think that continuity and conductivity alone of metal sheathing, as mentioned in the I.E.E. Wiring Regulations (No. 127B), sufficiently specify earthing circuits as applied to X-ray equipment. At the high frequencies observed in our work at Woolwich, discharges have been obtained from normally earthed circuits in the neighbourhood of X-ray equipment, and it is thought that every attempt should be made to afford as easy a path as possible for the removal of extraneous potentials. In the paper by Morgan and Taylor* a suitable size of metal strip for earthing electrodes is specified as 1 in. \times $\frac{1}{8}$ in.

In permanently fixed installations where comparatively short lengths of cable are employed and reliable earth bonding at both ends is effected, intermediate earthing tabs are not usually necessary. Such tabs, however, provide convenient points for earthing a cable on a portable equipment where frequently the whole length is not in use and some turns remain on the winding drum, thus making the cable-end earthing points inaccessible. Also, on jobs in which a portable set is used, good earths are not always available, so that a number of earths in parallel are valuable.

Oil immersion of cable ends is referred to in the paper as an aid to testing, and therefore for temporary working only; for these conditions varnish films have afforded very helpful protection.

A high cable capacitance is a disadvantage when the charging current to the capacitance is high and the consequent transformer voltage-drop also is high, with the result that the potential difference across the tube is reduced. With cables of high capacitance there is the risk, during periods of instability of the tube, of heavy discharges occurring unless resistors or chokes are employed to check them.

In connection with the cable's function (at the cathode pole) of carrying filament current the value of conductor

resistance is important. In a representative specimen of cable for use on a tube operating at 200 kV(P) the resistance of the inner and outer conductors respectively were 0.05 and 0.07 ohm per 100 yards. For 10 yards of cable carrying 5 amps., the total conductor drop would only be 0.06 volt, which is negligible. The diameter of the outer conductor is large so as to avoid excessive radial electrostatic stress; there is therefore plenty of room for adequate copper stranding to give high conductivity.

Mr. Bell's remarks are centred upon the "earth or insulate" controversy. I have discussed the point in some detail in the paper, particularly with respect to earthing of the control panel, and have shown the advantages in a non-shockproof equipment of an insulated control unit. If the insulation principle be adopted it must include all apparatus—the transformer secondary, the tube stand and fittings, the couch, the room floor, and the control table. The effective insulation of the controls, in view of the near-earth potential of the supply circuits, is a matter requiring some care. The conditions existing in an engineering shop do not permit complete insulation, and therefore earth-sheathed shockproof apparatus should be used. The control panel in this case would, of course, be solidly earthed.

I am aware of Dr. Wintz's conclusion that a constant-potential set is not as dangerous as a straightforward transformer set, but, as argued in the paper, the transformer backing of the condensers controls their voltage in accordance with transformer wave-form, thus constituting them sources of dangerous discharge.

Whilst appreciating Mr. Beetlestone's submission that the earth shielding for tubes which operate at 400 kV(P), 6 mA, offers some difficulties, I should like to point out that the Philips organization have a complete outfit (illustrated by lantern slide during the reading of the paper) for this voltage. The tube is ray-protected and enclosed in an independent casing with rectangular back and hemi-cylindrical front, which is 8 ft. 6 in. long, 2 ft. wide, and 2 ft. high. This casing surmounts an earthed casing containing the high-voltage generator. The generator is very small indeed for its voltage and comprises a novel circuit due to Dr. Bouwers, in which condensers and valves are employed. I do not think, like Mr. Beetlestone, that the subject of X-ray protection need encroach upon a paper devoted to electrical safety, except where the means of obtaining the former also solves the problem of the latter. One or two cases of this character are mentioned in the paper. The possibilities of continuously evacuated tubes for high powers are considerable, and I feel sure that given compact, trouble-free pumping gear this type of equipment will come into more general use.

I am glad that Mr. Beetlestone mentions the necessity of short-circuiting condensers after use. I agree that this is an important safety precaution for apparatus which is not shock-proof. A device for the purpose used in the Research Department, Royal Arsenal, Woolwich, was described some years ago in my paper on "The Electrical Equipment of X-ray Apparatus."*

I share Mr. Raphael's view that short-time-rated high-power transformers with good regulation would be helpful

* *Journal I.E.E.*, 1933, vol. 72, p. 515.

* *Journal I.E.E.*, 1928, vol. 67, p. 437.

in the development of small portable apparatus for X-ray work. The diminutive unit of Dr. Bouwers, mentioned by Dr. Mayneord and briefly described in the *British Journal of Radiology* (1934, vol. 7, p. 25), is perhaps a good step towards achievement in this direction.

I do not know what was the basis on which the International Regulations suggested that air should be changed 10 times an hour, but I presume the noxious effects of gases associated with high-voltage apparatus were in mind. Assuming that the dimensions of an X-ray room were 12 ft. \times 15 ft. \times 15 ft. and that two persons were in it, the figure 3 600 cub. ft. per hour per adult person given in textbooks for the amount of fresh air required under ordinary conditions for healthy life would involve 3 changes, and naturally the presence of a high voltage would make more frequent changes necessary.

With reference to the time required to cut off the supply in the event of operation of the safety relay, I am unable to give the exact figure for the instrument described in the paper, but suppose it would be about $\frac{1}{50}$ sec. This period is given by Mr. Beetlestone as the time required for the Metropolitan-Vickers high-voltage relay to trip out. As indicated in my paper, I have been unable to obtain data for the time required for dangerous muscular reactions to occur, but the fact that alternat-

ing current at 50 cycles per sec. gives severe shocks leads me to the conclusion that $\frac{1}{50}$ sec. is a sufficient time-interval for dangerous effects to be sustained.

I have made no measurements of potential gradients down the earthed sheaths of high-voltage cables when breakdown between core and sheath has occurred, but I do not think it possible that with small-power plant such as X-ray apparatus there would ever be sufficient current to maintain a dangerous potential difference. If the sheath and earth circuit resistance were an ohm or so the secondary current necessary to produce a potential difference of even a few volts would be equivalent to several hundred per cent overload. Moreover, the high reactance of the secondary would forbid current growth on such a scale. Breakdowns of cables investigated at Woolwich have either been small current leaks with earth potential well maintained on the sheath, or definite punctures which have immediately tripped out the breakers on the primary side.

In conclusion, I should like to thank contributors to the discussion for information on their experience in connection with this subject, and for their questions. In these days when X-ray apparatus which is perfectly safe from the electrical point of view is available, every encouragement should, I feel, be given to extend its use.

SOME CONSIDERATIONS IN THE DESIGN OF HOT-CATHODE MERCURY-VAPOUR RECTIFIER CIRCUITS.*

By C. R. DUNHAM, B.A.

(Communication from the Staff of the Research Laboratories of the General Electric Company, Ltd., Wembley.)

(Paper received 13th December, 1933.)

SUMMARY.

It is known that in mercury-vapour rectifier circuits certain important advantages may be obtained by the addition of a smoothing filter in which the first element is a choke. In this paper it is shown that the inductance of this choke has to be sufficiently great to ensure that at every instant at least one of the rectifying valves is passing current. A method of calculating the minimum value of inductance required, and some notes on the practical design of a choke, are given.

The hot-cathode mercury-vapour rectifier is pre-eminently suitable for providing direct-current output of the order of a few amperes at voltages covering a wide range. Although the use of this type of valve has become very common, very little consideration has, up to the present, been given to the more detailed theory of operation and design of the circuits in which it is used. The result is that, in the majority of cases, these valves are used in circuits where the fullest advantage of their properties cannot be attained.

This paper deals in particular with the design of the smoothing filter for a mercury-vapour rectifier circuit, and shows that it is necessary when using this kind of valve that the first element of the filter shall be an inductor, and not a condenser, as is the more usual practice. The following important advantages then accrue:—

- (1) The d.c. output voltage is independent of the load current taken, over a wide range.
- (2) The rectifier valves are protected from heavy peak currents, and therefore a given type of valve can give a much larger output current.
- (3) Freedom from the generation of unwanted high-frequency oscillations (radio interference) is assured.

The use of an inductor as the first element in a rectifier smoothing circuit has already been proposed by Dallenbaugh and Quimby,[†] who give some quantitative results obtained experimentally. It is, however, not clear how their results are to be adapted for circuits of other capacities. In the present paper the subject has been approached from the theoretical standpoint and results have been obtained which are applicable to all sizes of rectifiers, and which are borne out by experimental verification.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] *QST*, 1932, vol. 16, pp. 14 and 26.

INTRODUCTION.

For the purpose of an analytical investigation it is permissible to regard the hot-cathode mercury-vapour rectifier as a device which is totally non-conducting in one direction, whilst offering zero impedance to the passage of current in the opposite direction, except for a small voltage-drop across the valve (when passing current), which is required to maintain the gaseous discharge. The voltage-drop is constant, independent of the value of the current flowing, and is generally between 9 and 20 volts, according to the design of the valve and conditions of operation. When considering circuits in which the applied voltages are high, it is

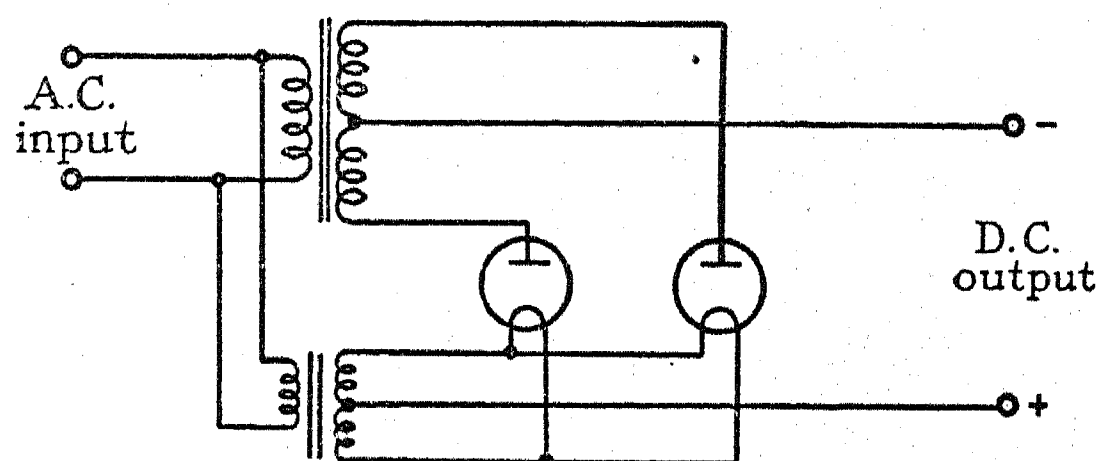


FIG. 1.—Biphas half-wave rectification circuit.

often permissible to neglect the voltage-drop, and the valve may then be taken as having zero or infinite impedance according to the direction of the resultant voltage in the circuit. In general, the voltage-drop may be accounted for in a theoretical consideration by assuming an opposing e.m.f. acting round the circuit during the period the current is flowing.

One of the most common types of rectification circuit met with in practice is the biphas half-wave circuit shown in Fig. 1. Sinusoidal voltages of equal amplitudes but of opposite phases, which may be obtained from two similar windings of a transformer, are applied to a common load through two rectifying valves. The load takes a unidirectional current which flows through each of the two valves alternately. Current may flow through either valve when, and only when, the potential of its anode with respect to the common point of the transformer winding is greater than the voltage existing in the load, plus the necessary 9–20 volts required to sustain a discharge in the valve. Current will therefore flow into the load alternately through each of the two valves, according to which has the higher instantaneous potential applied to the anode.

If the short-circuit impedance of the transformer

windings be assumed negligible, relative to that of the load circuit, it follows that current may flow through only one of the two valves at any instant; for otherwise a negative voltage-drop would occur in the valve with the lower instantaneous anode potential, which is inadmissible with the flow of current through it. When the short-circuit impedance of the transformer is not negligible a negative voltage-drop can be taken up by this impedance, so that there may exist two intervals per cycle, termed "overlap," when both valves are conducting, the length of this period being determined by the relative values of transformer and load impedance.

Hence there are three possible conditions at any instant:—

(a) *When current flows through one valve only.*—In this case the instantaneous voltage across the terminals of the load is equal to the instantaneous voltage developed at the terminals of the transformer winding connected to the conducting valve, less the small constant voltage required to sustain a discharge.

(b) *When current flows through both valves simultaneously.*—It can be shown that during the overlap the voltage across the load is equal to the mean of that developed in the two transformer windings, less the small constant "valve drop."

(c) *When neither valve passes current.*—Here the voltage across the load is determined solely by the characteristics of the load circuit, but is necessarily greater than the instantaneous voltage developed in either transformer winding, less the "valve drop."

EFFECT OF DIFFERENT TYPES OF LOAD CIRCUITS.

(a) Resistance Load.

When load consists of a pure resistance, Fig. 2, the voltage developed across the load must necessarily be equal to the product of its resistance and the current flowing through it: the current wave-form is the same as the voltage wave-form. It is observed that there are two intervals per cycle (when neither transformer winding voltage is sufficient to maintain a discharge in either valve) when no current flows through the load and the voltage across it is zero. If, however, the valve drop is small with respect to the transformer voltage (which is the case for transformer voltages of, say, 200 volts or more), these two intervals become negligibly small.

Neglecting the valve drop, then, it is seen that load voltage and current wave-forms consist of a sequence of sinusoidal half-waves and may therefore be expressed analytically in the form of Fourier series. Thus

$$v = \frac{4E}{\pi} \left\{ \frac{1}{2} + \sum_{n=1}^{\infty} \frac{\cos 4\pi n f t}{1 - 4n^2} \right\} \quad (1)$$

$$\text{and} \quad i = \frac{v}{R} \quad (2)$$

where E = peak value of the voltage generated in each transformer winding,

f = frequency of the a.c. supply,

R = resistance of the load,

v = instantaneous value of the load voltage,

and i = instantaneous value of the load current.

From the above it is at once seen that the mean (d.c.) output voltage and current are

$$v_m = \frac{2E}{\pi} = 0.636E \quad (3)$$

and

$$i_m = \frac{2E}{\pi R} \quad (4)$$

and in particular that the mean output voltage is independent of the load (current or resistance).

The peak value of the current flowing through either valve is

$$i_p = \frac{E}{R} = \frac{\pi}{2} i_m \quad (5)$$

Generally, however, the load cannot be regarded as consisting of a pure resistance; in many applications, for instance, it is necessary to secure a direct current and

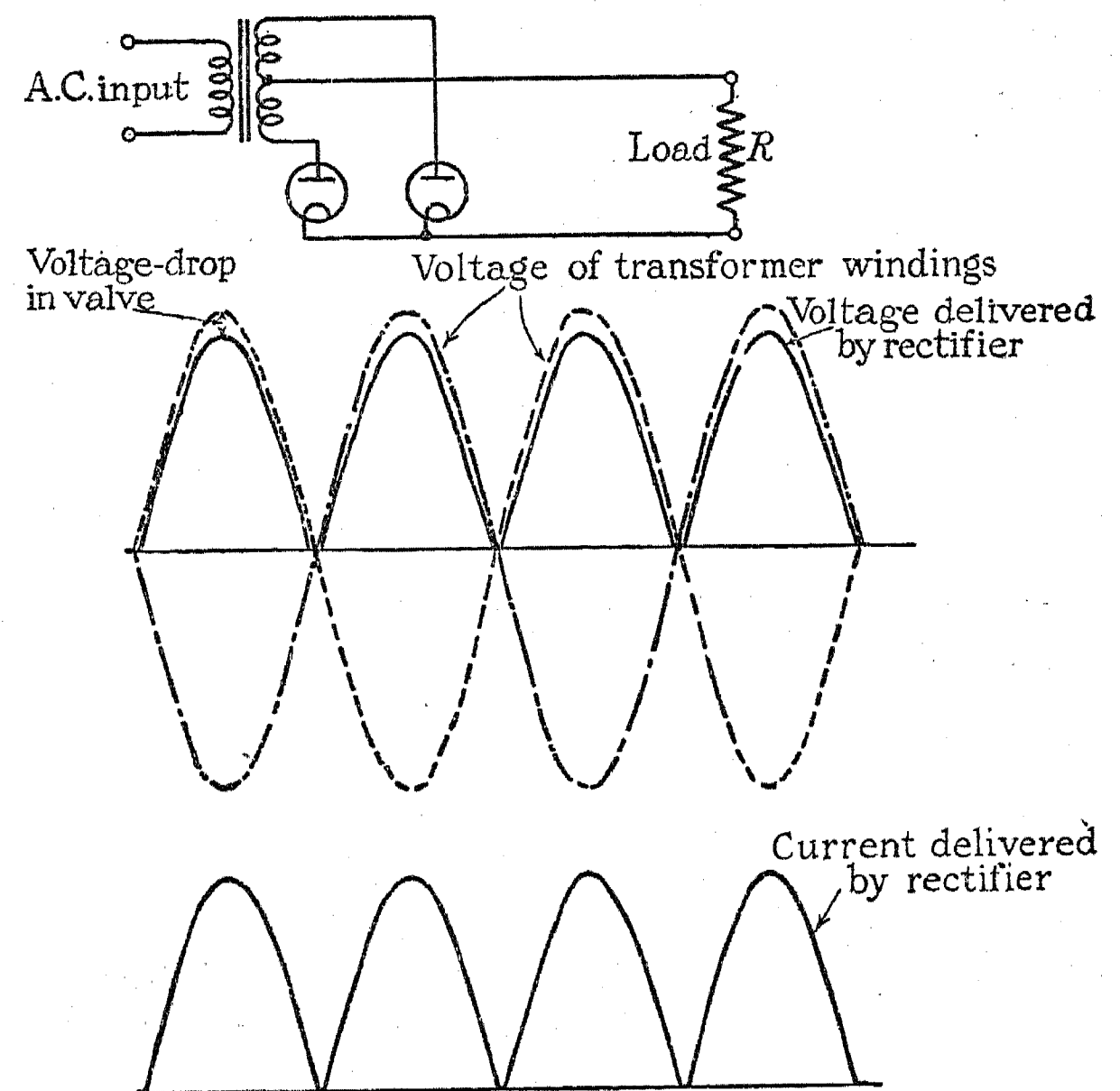


FIG. 2.—Biphase half-wave rectifier with pure resistance load.

output voltage substantially free from any superimposed ripple. For this purpose smoothing devices are usually incorporated between the rectifier circuit proper and the load circuit proper. These may be:—

(1) Condensers shunted across the load, which absorb energy by becoming charged during the peaks of the rectifier output voltage, and deliver this stored energy to the load during the intervals when the rectifier output voltage is low.

(2) Chokes in series with the load: the back e.m.f. generated in the choke opposes the fluctuations in the rectifier output voltage and tends to keep both load current and load voltage constant.

(3) Combinations of (1) and (2) above, in the form of "low pass filters" and, less frequently, "resonant harmonic filters."

(b) Capacitive Load, Voltage Soaring.

Fig. 3 illustrates the case where a condenser is shunted across the load for the purpose of reducing the ripple.

Current starts to flow through either valve when the corresponding transformer voltage exceeds that momentarily existing in the condenser (plus the valve drop), and continues to flow until the condenser becomes charged to a voltage equal to that of the transformer winding (less the valve drop), when conduction ceases. Subsequently the condenser voltage, and hence the load voltage, is determined by the rate of discharge of the condenser through the load resistance, until conduction through the other valve is set up during the next half-cycle. When current does flow through a valve its value is restricted mainly by the impedance of the transformer winding and can therefore be high; the period of conduction is consequently short.

It is most important to note that in this case the mean

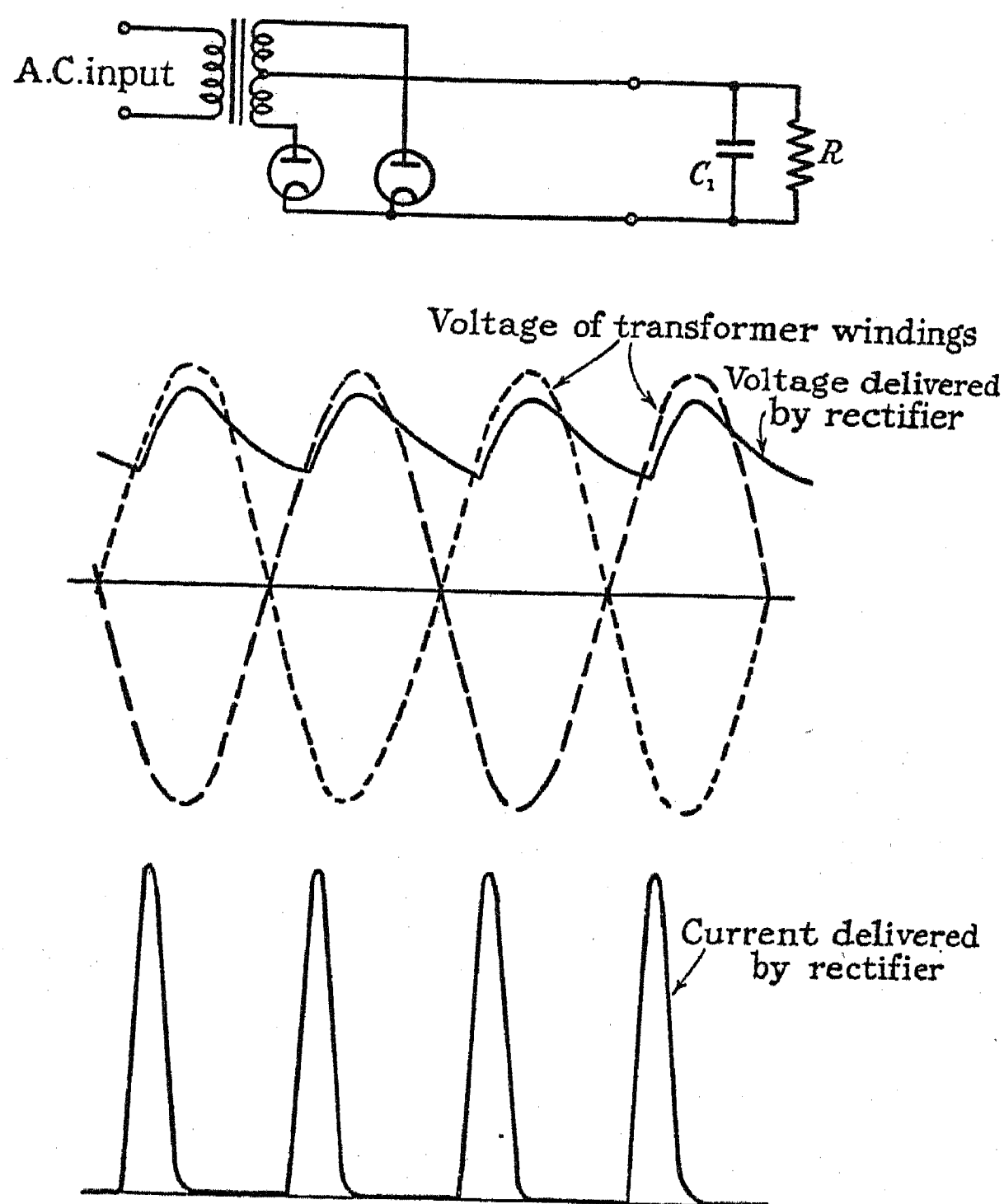


FIG. 3.—Biphase half-wave rectifier with capacitive load.

output voltage is greater than the corresponding value in the case of a pure resistance load. In certain cases advantage may be derived from this increased voltage, but since the duration of the conduction intervals is dependent on the load, it follows that the mean output voltage is also dependent on the load, and such a circuit will give a poor voltage regulation. A typical regulation curve of a rectifier feeding a capacitive load is shown in Fig. 8, curve B.

A more serious drawback to the use of a capacitive load circuit as in Fig. 3 lies in the fact that the anode current through each valve takes very high peak values. Since the peak anode current in a hot-cathode gasfilled valve has to be very definitely restricted by the liability of injury to the cathode, a high peak-to-mean ratio means that the output current must be restricted to a

low value for valves of a given type. The oscillogram in Fig. 9 gives some idea of the length of the conduction interval, and the ratio of peak anode current to the mean output current.

It is further to be noticed that when a circuit of this type is switched on after a period of rest, the condenser will be totally discharged. This will mean that for the first few cycles abnormally heavy peak anode currents will be taken in order to charge the condenser, irrespective of the value of the load current. This fact, then, must be counted as an additional disadvantage to the use of a smoothing circuit in which the first element is a condenser shunted across the load.

(c) Inductive Load.

When the load circuit may be regarded as consisting of an inductance in series with a resistance as in Fig. 4, the output voltage and current take wave-forms of the type shown. The effect of the added load inductance is to make the current through the load continuous. The current through each of the two valves therefore occupies at least half a cycle, and there may be (according to the value of the short-circuit impedance of the transformer windings) two overlap periods per cycle in which the two valves are simultaneously conducting. Neglecting these overlaps for the moment, however, it is clear that the output voltage of the rectifier, that is the voltage at the input to the choke, will be of the form of a succession of half sine waves, and therefore the mean output voltage will be

$$v_m = \frac{2E}{\pi} - e \quad \dots \quad (6)$$

where e represents the drop in voltage between anode and cathode in the conducting valve.

The effect of the existence of overlaps is to cause a small diminution in the mean output voltage, since, during a period when two valves are conducting, the effective voltage is equal to the mean of the two transformer voltages. In a biphas rectifier the overlaps are of short duration since commutation occurs at a time when the rate of change in the difference between the voltages generated in the two transformer windings (which is one of the factors determining the rapidity of commutation) is a maximum. The effect of overlaps on the mean output voltage of a biphas rectifier is therefore very small and can usually be neglected. This is, however, not true in the case of polyphase rectifiers, where the duration of the overlap increases with the load current and imparts to the circuit a definite regulation curve due to this effect alone.

Thus we see that if an inductance placed in series with the load is of sufficient magnitude to make the current taken from the rectifier continuous, the regulation curve will be flat, apart from the effect of overlaps (which is negligible in the case of a biphas circuit).

This principle, namely the introduction into the circuit of a choke of sufficient magnitude to make the current delivered by the rectifier continuous, and thereby ensuring a constant mean d.c. output voltage, is to be regarded as the basic feature of the following method of smoothing-circuit design.

RECTIFIER WITH SIMPLE FILTER CIRCUIT.

The addition to Fig. 4 of a shunt condenser across the load, as in Fig. 5, forms an efficient smoothing circuit which can be further improved by the addition of another filter section as in Fig. 6. Let us first consider theoretically the case of Fig. 5.

From the preceding section it follows that, provided the inductance L_1 is sufficiently great to ensure that a continuous current is taken from the rectifier, the regulation curve will be flat. If the inductance is not sufficiently great the voltage will soar at low output currents, owing to the presence of the condenser C_1 . It remains to determine what is the minimum value for the inductance L_1 in order to ensure a flat regulation curve.

In the limiting case when the inductance L_1 has its

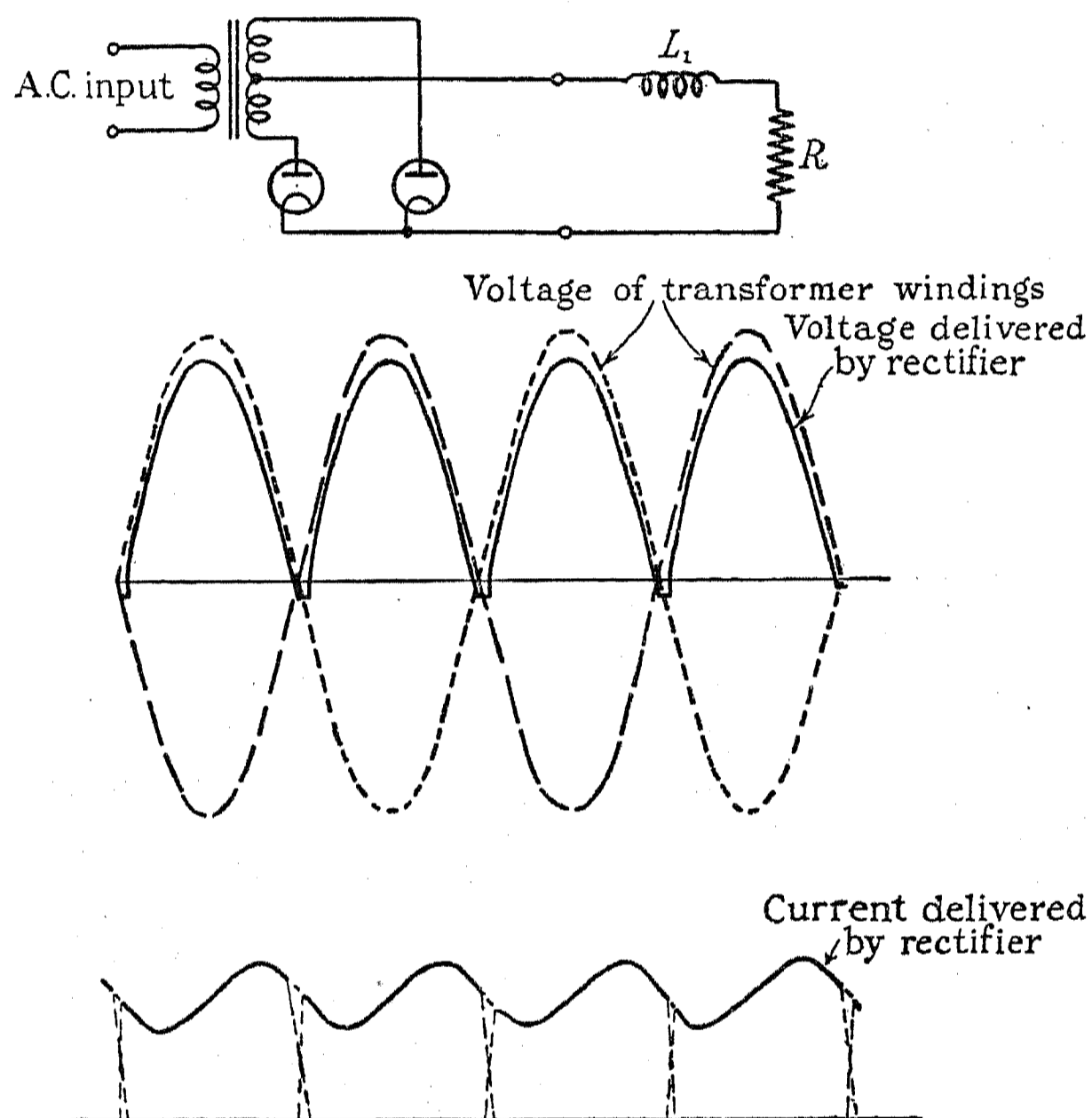


FIG. 4.—Biphase half-wave rectifier with inductive load.

minimum value, the current taken from the rectifier will be only just continuous, i.e. it will fall to zero momentarily twice per cycle. The output voltage waveform (i.e. across AB in Fig. 5) consists of a sequence of half sine waves and can be expressed in the form

$$v = \frac{4E}{\pi} \left\{ \frac{1}{2} + \sum_{n=1}^{\infty} \frac{\cos 4\pi nft}{1 - 4n^2} \right\} - e \quad (7)$$

and the current flowing into the load circuit at AB is

$$i = \frac{v}{Z} \quad (8)$$

where Z is the impedance of the load circuit at AB.

Since there is no dissipation in the smoothing devices L_1 and C_1 it follows that the mean d.c. output voltage and current in the load resistance are

$$v_m = \frac{2E}{\pi} - e \quad (9)$$

and

$$i_m = \frac{v_m}{R} = \frac{1}{R} \left(\frac{2E}{\pi} - e \right) \quad (10)$$

We have to find the condition that the current i is always greater than zero.

The current i may be regarded as the sum of a d.c.

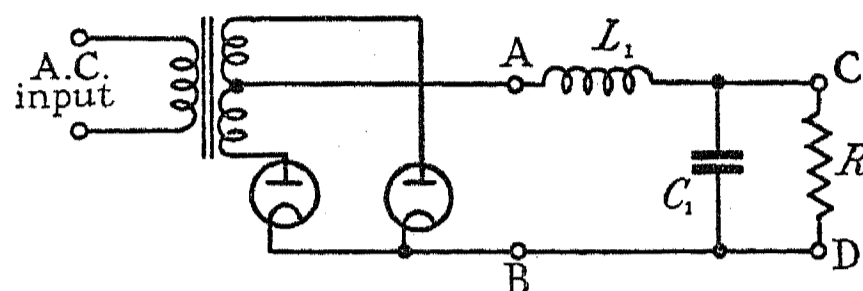


FIG. 5.—Biphase half-wave rectifier with single-section filter.

component equal to i_m plus several a.c. components of frequencies $2f, 4f, 6f, \dots$. The condition that i should always be greater than zero is equivalent to the condition that the d.c. component i_m should be greater than the maximum value of the sum of the a.c. components.

The magnitude of each a.c. component can be found by dividing the corresponding a.c. voltage component in the Fourier series for the voltage (equation 7) by the impedance of the load Z , at the relative frequency.

Now (i), The amplitude of the voltage components in equation (7) decreases in the sequence $\frac{1}{3}, \frac{1}{15}, \frac{1}{35}, \frac{1}{63}, \dots$, and

(ii), The impedance Z increases with frequency, since it is necessary that the load shall be inductive even at the lowest frequency in order to obtain smoothing.

It therefore follows that the amplitudes of the successive current components decrease very rapidly. Moreover, the Fourier series (7) for the voltage is one of cosines, that for the current must be one of sines, since the impedance is inductive; hence the maximum amplitude of the sum of the a.c. components must be almost exactly equal to the amplitude of the component of lowest frequency (since the maxima of the component sine functions do not occur together).

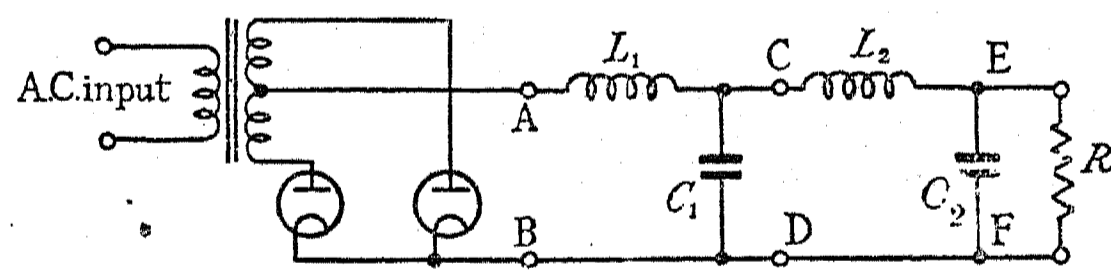


FIG. 6.—Biphase half-wave rectifier with two filter sections.

The impedance of the load circuit at AB is

$$Z = R \left\{ \frac{1 - 2\omega^2 L_1 C_1 + (\omega^2 L_1^2 / R^2) (1 + \omega^2 C_1^2 R^2)}{1 + \omega^2 C_1^2 R^2} \right\}^{\frac{1}{2}} \quad (11)$$

which at the frequency of the lowest harmonic, $2f$, becomes

$$Z_1 = R \left\{ \frac{1 - 8xy + 4x^2 (1 + 4y^2)}{1 + 4y^2} \right\}^{\frac{1}{2}} \quad (12)$$

where $x = \frac{2\pi f L_1}{R}$, and $y = 2\pi f C_1 R$.

Hence the amplitude of the lowest-harmonic current is

$$\frac{4E}{3\pi R} \left\{ \frac{1 + 4y^2}{1 - 8xy + 4x^2(1 + 4y^2)} \right\}^{\frac{1}{2}} \quad (13)$$

which is smaller than the d.c. component if

$$\left(\frac{2E}{\pi} - e \right)^2 > \frac{16E^2}{9\pi^2} \cdot \frac{1 + 4y^2}{1 - 8xy + 4x^2(1 + 4y^2)} \quad (14)$$

or

$$5 - 8\alpha - 16y^2(1 + 2\alpha) - 72xy + 36x^2(1 + 4y^2) > 0 \quad (15)$$

where

$$\alpha = \frac{\pi}{2} \cdot \frac{e}{E}$$

Now there are also other points to be considered in choosing values of x and y for a given circuit. First it is necessary that the combination of condenser and choke should at any rate cause some reduction in the ripple, for otherwise they would be a useless addition to the circuit. This requires that the harmonic of frequency $2f$ should have a lower voltage across CD than across AB in Fig. 5. This requires that

$$\omega L_1 > \frac{2\omega C_1 R^2}{1 - \omega^2 C_1^2 R^2} \quad \text{for } \omega = 2\pi \cdot 2f$$

or

$$x > \frac{2y}{1 + 4y^2} \quad (17)$$

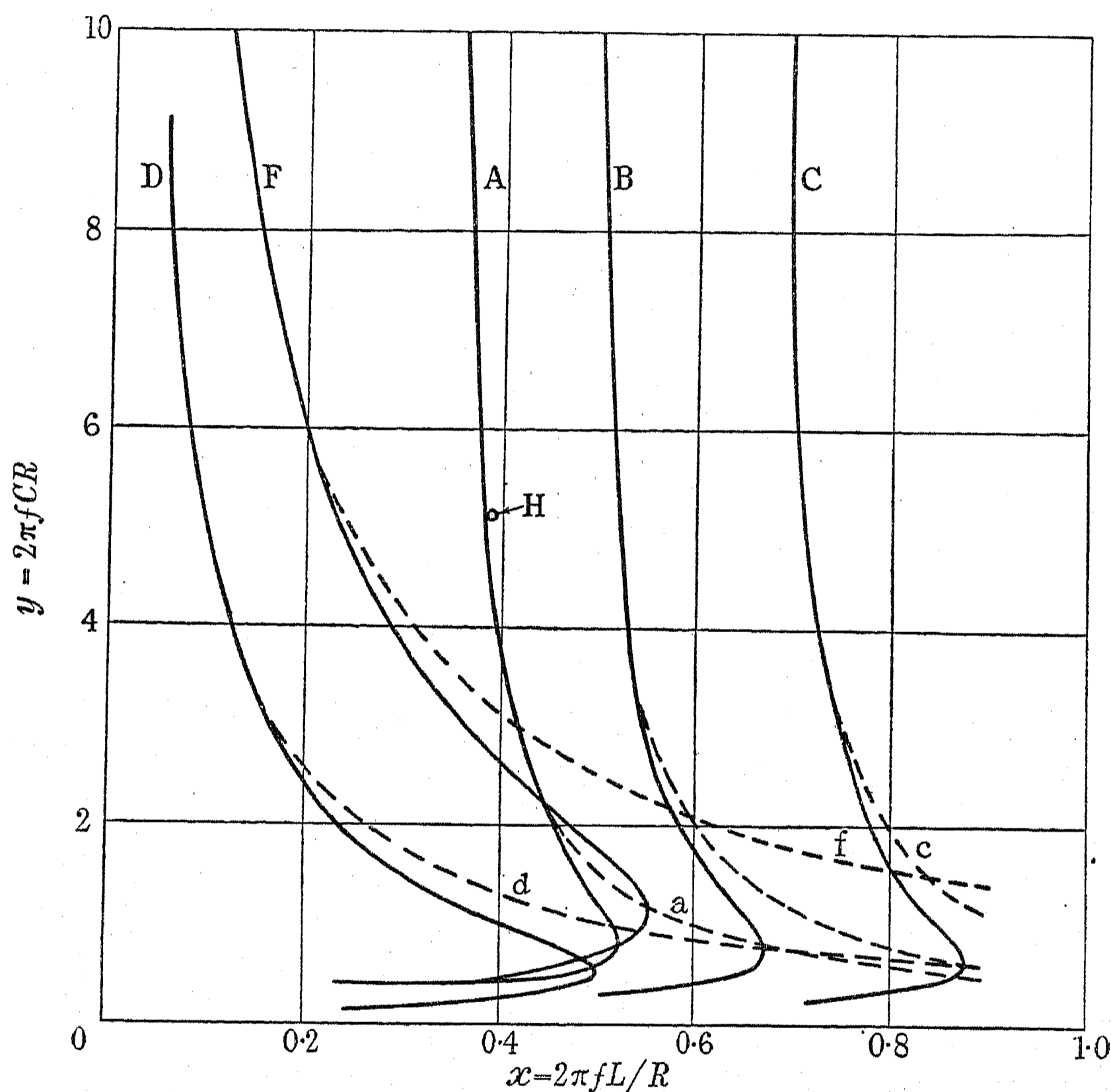


FIG. 7.—Fundamental curves for design of biphas half-wave rectifier.

- A.—Curve for good regulation. Peak-current/mean = 2.
- B.—Peak-current/mean = 1.71.
- C.—Peak-current/mean = 1.5.
- D.—Curve for ripple reduction.
- F.—Load resonance at 0.9 × supply frequency.

Full curves are for single-section filter; dotted curves are for double-section filter with $L_2 = \infty$.

Now when the transformer voltages are high the value of α becomes negligible. For instance, when the transformer windings each have an r.m.s. voltage of 1 000 volts, assuming e , the valve drop, to be 15 volts, α takes the value of 0.017. Neglecting α , then, the expression may be written

$$5 - 16y^2 - 72xy + 36x^2(1 + 4y^2) > 0 \quad (16)$$

This inequality is shown as curve A in Fig. 7. For a given value of y it is necessary that the value of x should lie to the right-hand side of this curve.

This means that values of x and y must be chosen to lie to the right of curve D in Fig. 7.

A further condition which has to be met is that the load circuit does not resonate at or about the supply frequency. Should such a resonance occur, an instability is set up in which the load is unequally divided between the two valves, and also between the two transformer windings, which is undesirable on both counts. It can, however, be taken as satisfactory if the resonance of the load circuit be 10 per cent removed from the supply frequency. If the load current taken is to be constant,

it does not matter whether the resonance be higher or lower than the supply frequency, but in the case where the load current is to be varied, owing to alteration in the load resistance (the rest of the circuit remaining unaltered), it is essential that the resonance of the load circuit be below the supply frequency at all loads. For condition (16) demands this at light loads, and we must avoid passing through a resonance as the load is increased. It therefore follows that, in a rectifier to supply a varying load, values must be chosen for x and y corresponding to a point to the right of both curve A, the good-regulation curve, and also curve F, the load-circuit resonance curve for a frequency 10 per cent below that of the supply.

EFFECT OF ADDITION OF FURTHER SMOOTHING-FILTER SECTIONS.

Very often the use of a single choke and a single condenser will not be adequate to obtain the required reduction in ripple in the d.c. output. The addition of a further filter section consisting of a second choke L_2 and a second condenser C_2 , as in Fig. 6, will be necessary. The effect of the choke L_2 will be to increase the impedance of the load circuit at EF for all ripple frequencies without changing its d.c. resistance. The limiting case will be when the inductance of L_2 is infinite. This case is capable of a very simple mathematical analysis, and we shall know that the solution of the practical case will lie somewhere between this and that of the previous paragraph.

When the second choke L_2 has infinite inductance, the impedance of the load circuit at AB will be

$$R \text{ to a d.c. voltage, and } j\omega L_1 + \frac{1}{j\omega C_1} \text{ to an a.c. voltage of frequency } \omega/(2\pi) \quad (18)$$

Following then the theory of the previous pages, we have, instead of inequality (15),

$$12xy - \frac{4y}{1-\alpha} - 3 > 0 \quad (19)$$

or neglecting α , as before,

$$12xy - 4y - 3 > 0 \quad (20)$$

This inequality is shown in Fig. 7 as the dotted curve a.

Similarly, instead of curves D and F we have the dotted curves d and f, whose equations are

$$x = \frac{1}{2y} \quad (21)$$

$$\text{and } 0.9x = \frac{1}{0.9y} \quad (22)$$

It is to be noted that the three new curves do not depart appreciably from their prototypes in the single-section case except for small values of y (which do not concern us). Hence we may use either of these two sets of curves for the practical case where L_2 has a finite inductance.

CHOICE OF VALUES FOR FIRST CHOKE AND FIRST CONDENSER.

From examination of Fig. 7 it is seen that the minimum value of x permissible in order to get a flat regulation curve is 0.33 for a large value of y , but that by increasing x to 0.425, y may be reduced to 3. y can thence be only further reduced by a relatively large increase in x . In the case then where the rectifier has to give a constant output current, suitable values of x and y would be

$$\left. \begin{aligned} x &= 0.425 = \frac{2\pi f L_1}{R} \\ y &= 3 = 2\pi f C_1 R \end{aligned} \right\} \quad (23)$$

giving the required inductance and capacitance in terms of the load resistance and the frequency.

When the rectifier has to supply a varying load it is, of course, necessary that the points (x, y) should lie to the right of curve A for all values of R taken. Supposing the values of capacitance and inductance to remain unchanged as R is varied, then x will be inversely, and y directly, proportional to R , and the locus of the point (x, y) will be a hyperbola asymptotic to the two axes. It is clear then that there will be a maximum value for R , i.e. a minimum load current, where this locus cuts curve A. Above this minimum load the required condition of continuity of anode current will be satisfied and the regulation curve will be flat, while below it the voltage output will soar.

In order to obtain a flat regulation curve down to lower currents, it is necessary to increase the value of the inductance. Now, as will be described later, it is possible to construct an iron-cored choke which has the property that its inductance is, over a wide range, inversely proportional to the direct current passing through it. This is exactly what is required for a rectifier which has to feed a varying load. The value of x is independent of R , and it is necessary to design the choke so that $x \leq 0.425$, and choose a condenser so that at the maximum load $y \leq 3$.

With an iron-cored choke of this design it is possible to construct a rectifier which gives a flat regulation curve over a variation of load current of 0.05 to 1. It is obviously impracticable to obtain a flat regulation curve down to zero load, since this would require an infinite inductance, but the range obtainable by use of an inductance of the minimum value given above represents an immense improvement over the regulation curves hitherto obtained. If it is essential that voltage-soaring should be prevented at zero load, a small permanent load of 0.05 maximum load may be shunted across the output. An output voltmeter permanently connected might, for instance, provide a sufficient load to prevent voltage-soaring.

PEAK CURRENT.

When values of inductance and capacitance for the first choke and condenser are so chosen that the point (x, y) lies on curve A in Fig. 7, then we know that the maximum value of the current flowing through either anode is equal to twice the mean d.c. output current. In certain cases, where it is required to obtain the most

efficient use of the valves by loading them up as much as the cathode emission will permit, it may be advisable to increase the inductance of the choke L_1 , and thereby reduce the peak value of anode currents. Thus, if it were required to reduce the peak value of anode current to 1.5 times the mean output current, it would be necessary to reduce the amplitude of the harmonic ripple to half the mean direct current. This would require

$$\left(\frac{2E}{\pi} - e\right)^2 > \frac{64E^2}{9\pi^2} \cdot \frac{1 + 4y^2}{1 - 8xy + 4x^2(1 + 4y^2)} \quad (24)$$

or

$$-7 - 32\alpha - 64y^2(1 + 2\alpha) - 72xy + 36x^2(1 + 4y^2) > 0 \quad (25)$$

in the case of a single-section smoothing circuit, or

$$12xy - \frac{8y}{1 - \alpha} - 3 > 0 \quad (26)$$

in the case of a double-section smoothing circuit when L_2 is infinite.

Curves C and c corresponding to these inequalities have been drawn for $\alpha = 0$ in Fig. 7. Similar curves B and b refer to a ratio of peak anode to mean output current of 1.707 to 1.

In general it will only be necessary to consider the curves B or C at the maximum output of a rectifier circuit. At lower outputs, where the peak anode rating of the tube will not be approached, it will be sufficient to use curve A in order to get good regulation.

EXAMPLE.

As an example of the use of Fig. 7, let us consider the design of a rectifier circuit to give a maximum d.c. output of 1 ampere at 1 000 volts, the peak rating of the valves to be used being 1.5 amperes, and the supply frequency 50 cycles per sec.

First, equation (9) tells us that the r.m.s. voltage of each half of the transformer winding will be 1 125 volts (assuming e to be 15 volts).

Now for loads of less than 0.75 ampere a peak-to-mean ratio of 2 to 1 is permissible, and therefore curve A may be used in designing the circuit for this range. At a load of 0.75 ampere, R has the value of 1 333 ohms, and x and y must be not less than 0.42 and 3, respectively, from Fig. 7. The condenser C_1 must therefore have a capacitance of 7.15 μ F, and an inductance of 1.78 henrys when carrying 0.75 ampere (d.c.).

At a load of 0.5 ampere R has the value 2 000 ohms. With the same condenser y is 4.5, and x must therefore be 0.39, giving a required inductance of L_1 of 2.48 henrys when carrying 0.5 ampere (d.c.). At lower values of load current the inductance necessary increases approximately in proportion to the resistance of the load.

At a load of 0.88 ampere the permissible peak-to-mean ratio is 1.7 to 1, and curve B must be used. y has now the value 2.56, and x must therefore be 0.57, requiring an inductance of 2.06 henrys.

At a load of 1 ampere the permissible peak-to-mean ratio is 1.5 to 1, and curve C must be used. y has now the value of 2.25, and x must therefore be 0.78, requiring an inductance for L_1 of 2.48 henrys.

It therefore remains to design a choke L_1 such that it has the following minimum inductance values:—

- 2.48 henrys when carrying 1 ampere (d.c.)
- 2.06 henrys when carrying 0.88 ampere (d.c.)
- 1.78 henrys when carrying 0.75 ampere (d.c.)
- 2.48 henrys when carrying 0.5 ampere (d.c.)
- 4.58 henrys when carrying 0.25 ampere (d.c.)
- 11.1 henrys when carrying 0.1 ampere, and so on.

EFFECT OF VOLTAGE-DROP IN VALVES ON VALUE OF INDUCTANCE REQUIRED.

When the transformer voltage is low, or the rectifier has to supply a load in opposition to some back voltage such as a battery or d.c. motor, it is no longer legitimate to neglect the value of α in inequality (15), etc. In any particular example, knowing α , it will be possible, though somewhat laborious, to work out these inequalities. If, however, we take the inequality (19) referring to the two-section case, which we have seen is practically identical with (15) over the range of x and y which concerns us, the effect of taking into account a small value of α can be seen at once by writing (19) in the form

$$\begin{aligned} x &= \frac{1}{3(1 - \alpha)} + \frac{1}{4y} \\ &= \frac{1}{3}(1 + \alpha) + \frac{1}{4y} \text{ (approximately) } \quad (27) \end{aligned}$$

Thus for small values of α the value of x must be increased uniformly by $\alpha/3$ over the value for curve A.

For points on curve C, x must be similarly increased by $2\alpha/3$, and on curve B by 0.471α .

Thus in the previous example, where

$$\alpha = \frac{\pi \cdot e}{2 \cdot E} = \frac{\pi \cdot 15}{2 \cdot 1125} = 0.0167$$

the values of inductance necessary should be increased to

- 2.51 henrys at 1 ampere (d.c.)
- 2.08 henrys at 0.88 ampere (d.c.)
- 1.80 henrys at 0.75 ampere (d.c.), and so on;

in this case a trifling alteration.

EXPERIMENTAL VERIFICATION.

In order to test the validity of the preceding argument a series of experiments was made, and a number of regulation curves and oscillograms were taken which prove conclusively that the theory is sound.

A biphasic half-wave rectifier was made up using a shell-type transformer with two secondary windings each of 500 volts (r.m.s.). The valves employed were Osram G.U.1 mercury-vapour rectifiers.

The first test consisted of taking a regulation curve of the output voltage against current, when the load consisted of a pure resistance, i.e. using the circuit shown in Fig. 2. The curve obtained is shown as curve A in Fig. 8. The slope of this curve is, of course, determined by the resistance of the transformer windings.

Curve B (Fig. 8) was obtained when a 20- μ F condenser

was shunted across the load as in Fig. 3, and clearly illustrates the effect of the condenser in producing voltage-soaring and bad regulation. Fig. 9 is a copy of an oscillogram taken under this condition, and gives a good idea of the length of conduction time in each valve and the heavy peak currents through them.

Curve D (Fig. 8) was obtained when a first choke

tively. At the critical output current (0.54 ampere), where the current delivered by the rectifier is just continuous, we have $R = 818$ ohms, and therefore $x = 0.384$ and $y = 5.14$. Referring to Fig. 7, these values correspond to the point H, which lies almost exactly on the curve A, thus proving the soundness of the preceding theory.

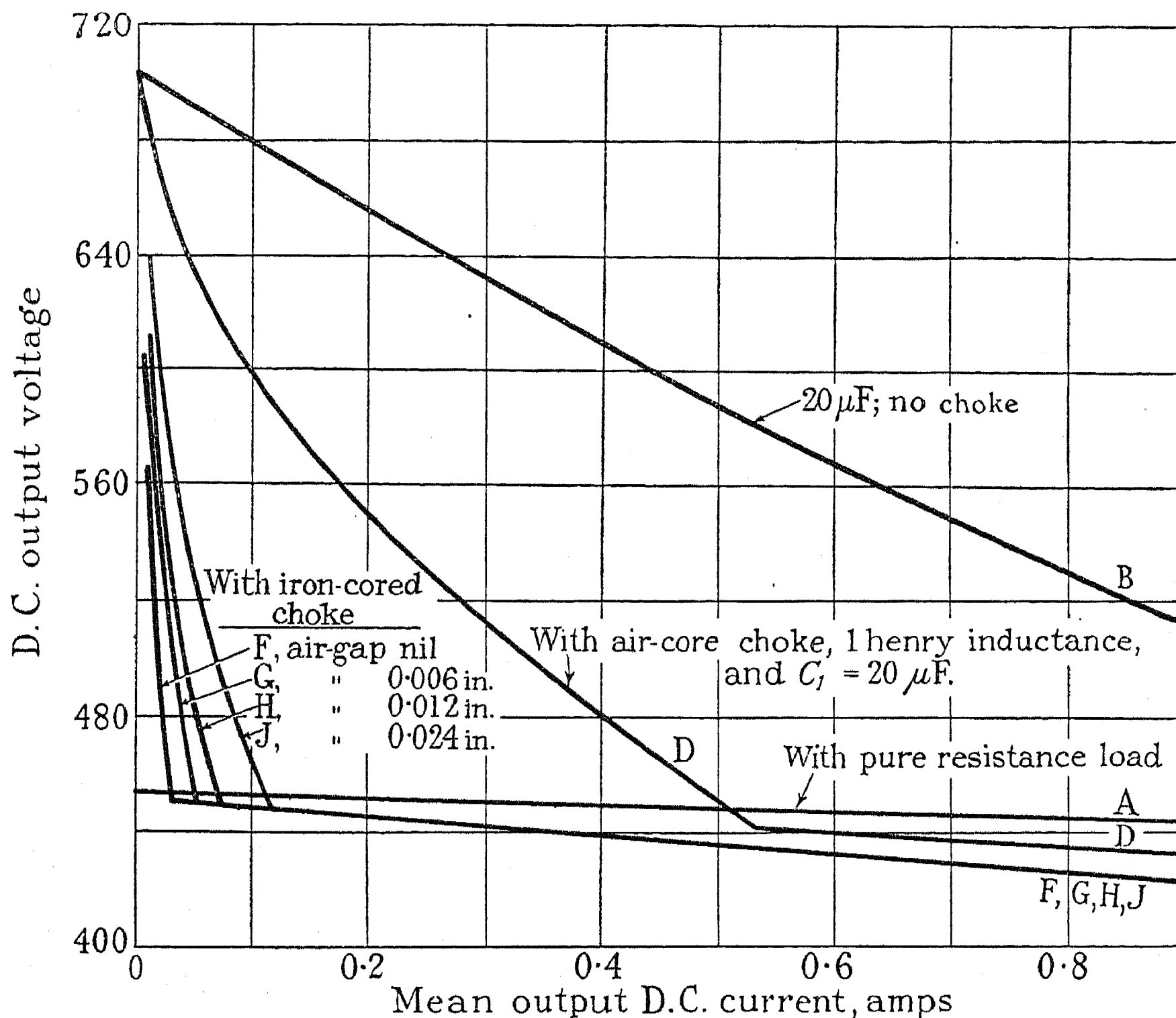


FIG. 8.—Regulation curves of biphas half-wave rectifier (transformer voltage 500 + 500).

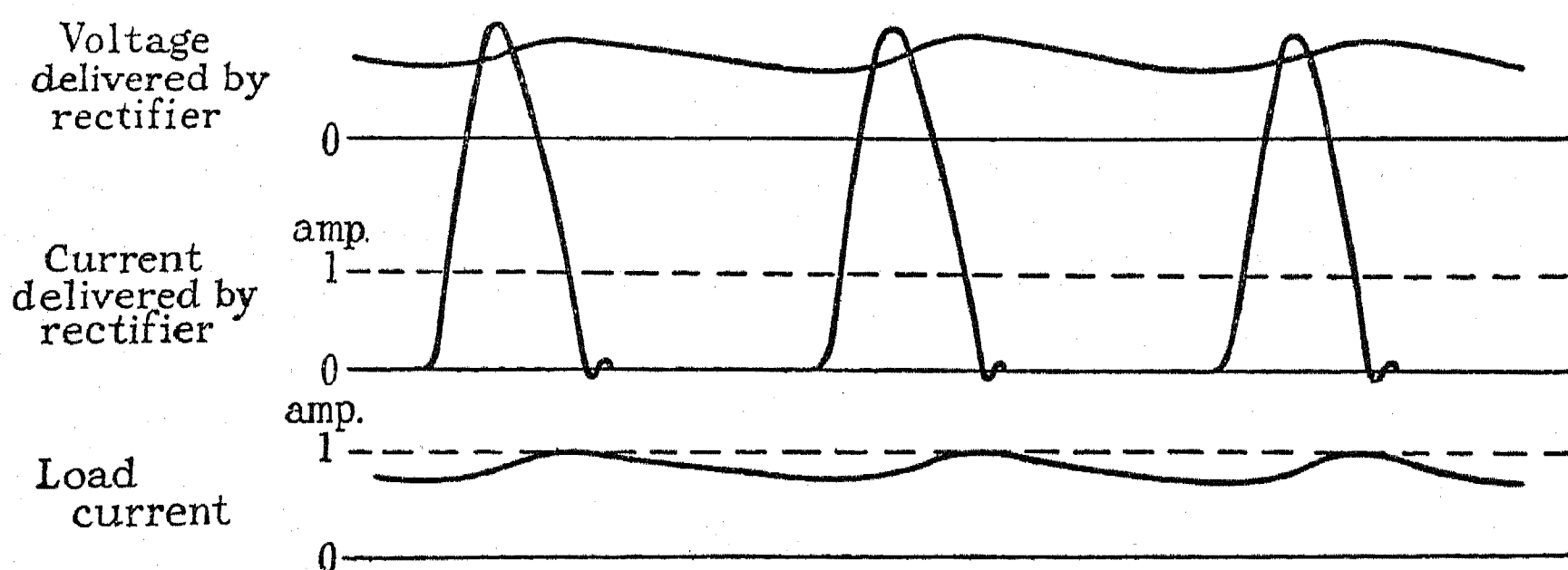


FIG. 9.—Oscillogram. Resistance load shunted by 20-μF condenser. Mean output current 0.8 ampere.

consisting of a 1-henry air-core inductance was used, followed by a 20-μF condenser. From this curve it follows that the choke is sufficiently great to ensure that a continuous current be taken from the rectifier for all values of output current above 0.54 ampere, but not for values below. This is also to be seen in the oscillograms of Fig. 10, which were taken for mean d.c. output currents of 1, 0.8, 0.6, 0.5, 0.4, and 0.2 ampere respec-

A further point which is to be observed from the first three oscillograms of Fig. 10 is that the current delivered by the rectifier is almost exactly sinusoidal. This means that the current which passes through the first choke consists of a d.c. component and only one a.c. component of frequency $2f$. This is the result arrived at theoretically on page 281.

In the last three oscillograms in Fig. 10, where the

current delivered by the rectifier is discontinuous, a sharp rise in output voltage due to the charge on the condenser is observable at the moment when the valve current ceases. This sharp rise in voltage causes an oscillation in the circuit components which is clearly visible in the oscillograms. Unwanted oscillation of this type in practice sometimes gives rise to trouble from interference. When, however, the current delivered by the rectifier is made continuous, the generation of unwanted oscillations is made impossible, since sudden voltage-changes in any part of the circuit do not occur.

The remainder of the curves of Fig. 8 were taken with a first choke which consisted of 1 780 turns of No. 20

full-wave working an identical result will be obtained with that given by biphas half-wave working.

PRACTICAL DESIGN OF A SMOOTHING CHOKE WITH AN IRON CORE.

The practical design of the first smoothing choke falls into one of two main cases, according to the service required from the rectifier. If the rectifier is always to deliver a constant load current, it is merely necessary to design the choke to have a certain minimum inductance at that current. A suitable method of design for this case is given by C. R. Hanna.* The substance of this

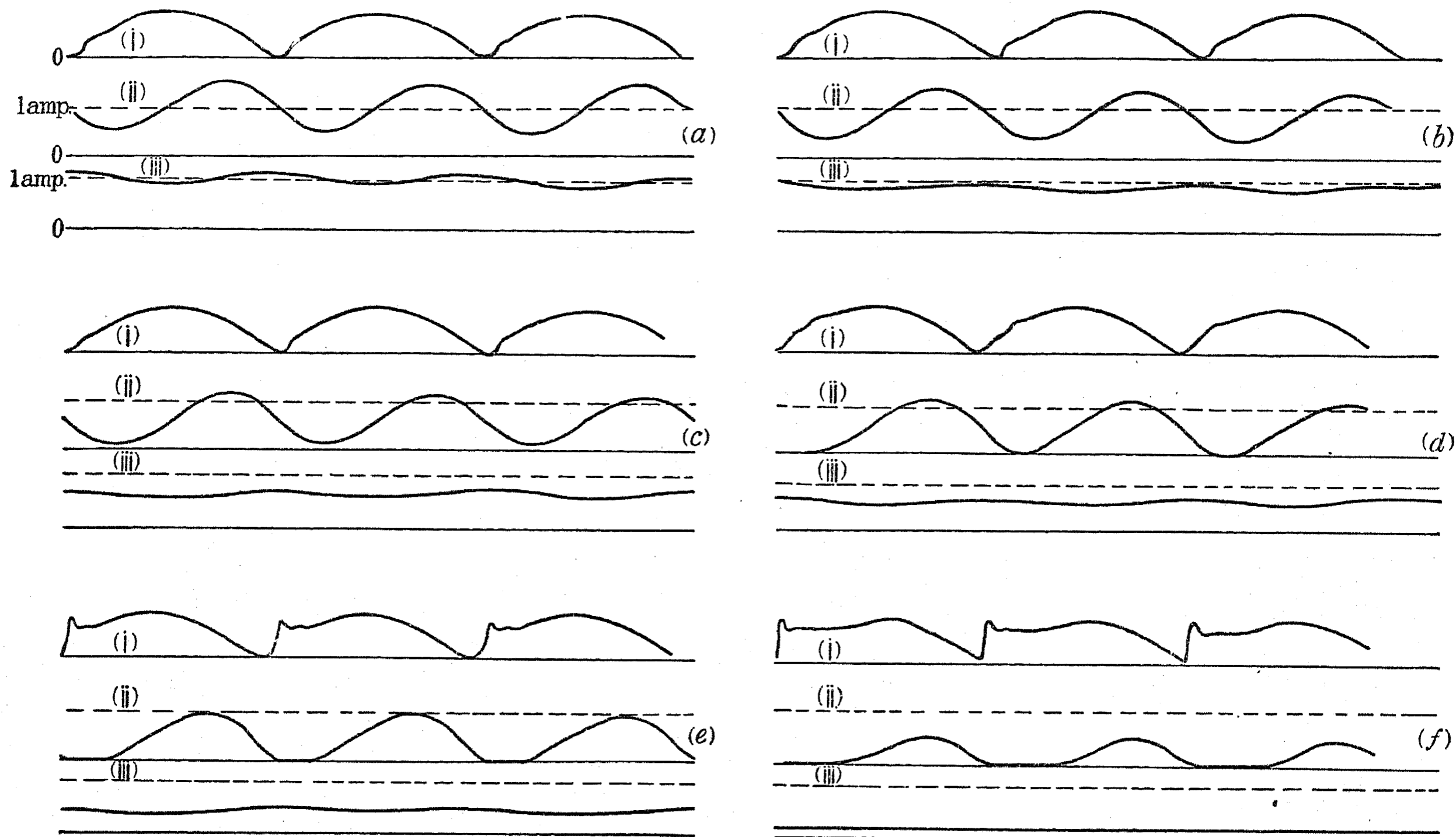


FIG. 10.—Oscillograms.

$L_1 = 1$ henry (air-cored); $C_1 = 20 \mu\text{F}$.

(i) Voltage delivered by rectifier.

(ii) Current delivered by rectifier.

(iii) Load current.

Mean output current:—(a) 1 amp., (b) 0.8 amp., (c) 0.6 amp., (d) 0.5 amp., (e) 0.4 amp., (f) 0.2 amp.

S.W.G. d.s.c. copper wire wound on a stalloy core of 100 pairs of Sankey's No. 28 stampings (gross sectional area $1\frac{1}{2}$ in. \times $1\frac{1}{4}$ in.), and a condenser of $20 \mu\text{F}$. From these curves the very great improvement in regulation obtainable by the use of an iron-cored choke is at once apparent.

APPLICATION TO MULTI-PHASE CIRCUITS.

Although in this paper the case of a biphas half-wave rectifier has been considered exclusively, the theory is equally applicable to multiphase and full-wave working, it only being necessary to use in equation (7) the Fourier series for the harmonics in the case to be dealt with. It is at once obvious that in single-phase

paper has been rearranged in a very convenient form for design purposes in Fig. 25 (a, b, and c) of the *Wireless World* "Radio Data Charts" by Dr. R. T. Beatty. It is to be noted that this design is based on a core material of 4 per cent silicon steel, an American alloy. It is, however, known by experiment that the design data given are also sufficiently correct for cores of stalloy. This is to be expected (even though the permeabilities shown for stalloy and 4 per cent silicon steel are different), since the inductance and saturation of the core will be mainly determined by the size of the air-gap.

When, however, the rectifier is required to deliver a variable load current, it is necessary that the inductance

* C. R. HANNA: *Transactions of the American Institute of Electrical Engineers* 1927, vol. 46, p. 155

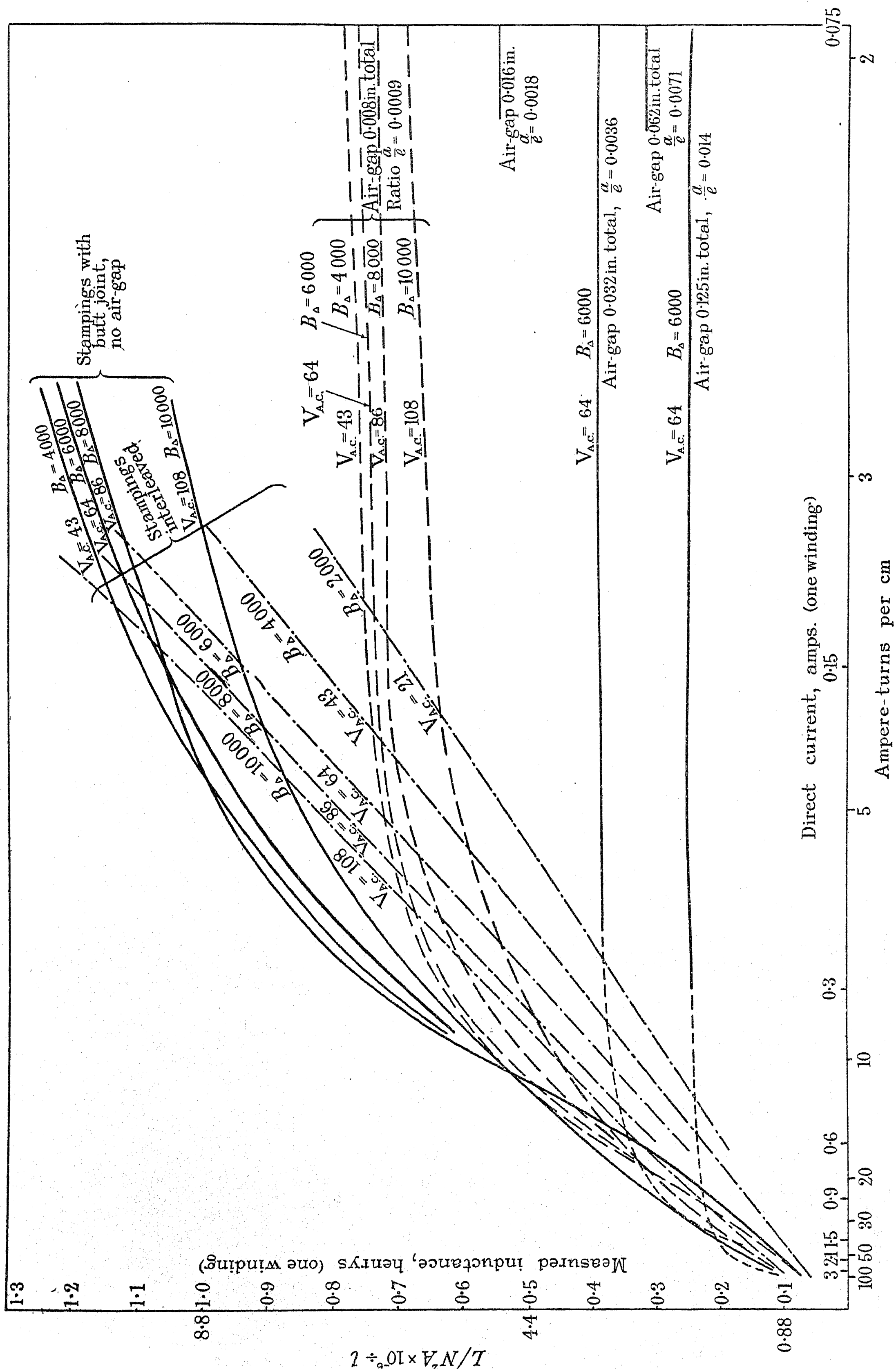


FIG. 11.—Measured inductance of iron-cored choke with different air-gaps and various values of applied a.c. voltage (50 cycles per sec.).

of the choke L_1 should have certain minimum values of inductance over the given range of direct current. In general, a choke built on the design referred to above will not satisfy this requirement. In particular, it would not have sufficient inductance at low direct currents.

Roughly speaking, what is required is that the value of inductance shall be inversely proportional to the d.c. load, but at heavy currents it may be advisable to increase the inductance in order to reduce the peaks in the anode-current wave-form. Obviously, the most economical choke would just have this minimum value of inductance over the range of direct current to be carried. It therefore remains to be seen whether such a condition can be arranged, by suitable choice of winding, core, and air-gap.

Since little information is obtainable regarding the behaviour of iron under different conditions of superposed d.c. and a.c. fields (and, even if it were, the design of a choke by calculation alone would be a formidable task), the inductance of a choke was measured under different conditions. The choke measured consisted of two separate windings, each of 575 turns of No. 22 S.W.G. (0.028 in.) d.s.c. copper wire, wound on a core of 100 pairs of No. 4 Sankey's stalloy stampings, giving a gross sectional area of 1.5 in. \times $\frac{1.5}{16}$ in., or 8 cm² net, allowing 12 per cent for insulation, with an iron-circuit length of 22 cm. One of the windings was arranged to carry direct current alone (it being placed in series with a 60-henry choke to stop induced alternating currents), and the inductance of the other winding was determined by measuring the current when subjected to an a.c. voltage at 50 cycles per sec. The results are given in Fig. 11, in which each curve shows the inductance of one winding (for a given air-gap and given applied a.c. voltage) plotted against the inverse of the direct current in the other winding. On the same figure are shown scales of ampere-turns per cm, and inductances divided by N^2A/l (A = net area of core; l = length of iron circuit) which are applicable to chokes of other dimen-

sions, provided the same ratio of air-gap to iron-circuit path length is kept, irrespective of whether the direct and alternating currents flow through the same or different windings.

From Fig. 11 it is at once seen that when the air-gap is zero the inductance of the choke varies with the direct current carried in the required manner, and at first sight it would seem that such a design would be satisfactory. Since for a given value of direct current the inductance increases with the value of a.c. voltage applied, however, the choke would not be effective in the rectifier circuit, as it would tend to operate, presenting the lowest value of inductance and a.c. voltage across its terminals. When an air-gap is introduced into the iron circuit, however, the conditions are changed. For a given value of direct current, the inductance of the choke is much more nearly constant, and what variation there is, with respect to applied a.c. voltage, is in the opposite direction. The inductance at very low values of direct current is, of course, decreased.

It is therefore necessary to strike a mean between a too-large air-gap, which gives insufficient inductance at low values of direct current, and a too-small air-gap, which causes loss of inductance owing to incorrect characteristic. In the case of a choke of the size under consideration, probably an air-gap of about 0.004 in. (total) would be the most useful.

From the curves of Fig. 11 a choke for any given rectifier can be designed, by using the alternative scales given. It is necessary to keep the same ratio of air-gap to iron-circuit length, and to make sure that the a.c. voltage per turn applied gives rise to a value of δB not greater than about 8 000. It is to be remembered that the measurements of Fig. 11 were taken with an applied alternating current at 50 cycles per sec.; in a rectifier circuit we shall be dealing with the first harmonic, which will usually be of higher frequency. It is then a matter of choosing the right size of core and the correct number of turns in order to get the required inductance values over the given range of direct current.

INTERNATIONAL FREQUENCY COMPARISONS BY MEANS OF MODULATION EMISSIONS.*

By L. ESSEN, B.Sc.

[From the National Physical Laboratory.]

(Paper first received 6th December, 1933, and in final form 19th February, 1934.)

SUMMARY.

The results of early international comparisons of frequency are briefly discussed. In measurements carried out in 1925 the agreement obtained was 0.1 per cent, and in 1929 an agreement of 0.006 per cent was realized. At this time the frequencies of the standards at several laboratories could be determined absolutely with an accuracy greater than that with which the comparisons could be effected.

The nature of the recent modulated emissions is described and the results of three of the emissions are given. In two of the comparisons, measurements made at three different laboratories are in agreement within 1 part in 10^7 .

An experiment is described showing that the frequency of modulation of an aerial current can be controlled by a distant standard with an accuracy of at least 2 parts in 10^8 ; and that the frequency measurements can be effected with this order of accuracy.

(1) INTRODUCTION.

With the rapid development of radio communication one of the duties of the national laboratories was to develop and maintain frequency standards by means of which measurements could be made on the frequencies of the numerous transmitters in operation. As the range and power of stations increased it became of importance to compare the standards of different countries in order to avoid interference in international communications. In 1925 a comparison between the American, English, and German, standards was effected by the three national laboratories making simultaneous measurements of the frequencies of selected transmitters in terms of the frequencies of their standards. It appeared from these measurements that the standards were in agreement to about 0.1 per cent, which was considered to be fairly satisfactory at the time. In 1929 a quartz oscillator was taken by Dr. Jolliffe of the Bureau of Standards to the various European laboratories, and an agreement of 0.006 per cent was obtained between the values assigned to it in France, Italy, Germany, England, and America. Similar measurements made during 1929 and 1930 of the frequency of a quartz resonator agreed to within 0.0015 per cent.† By this time some of the laboratories possessed the means of determining the frequency of their standard

oscillator in terms of the mean solar second with an accuracy of 10 parts in 10^6 (0.001 per cent). The international comparisons therefore served to check the errors of measurement and the constancy of frequency of the oscillators and resonators used for the comparisons, rather than the fundamental standards themselves. They were still of importance from this point of view.

Most of the uncertainties of measurement were introduced by the unavoidable use of an auxiliary oscillator. This oscillator was calibrated by the local standard at points as near as possible to the frequency being measured, the value of which was then calculated by interpolation. These errors are eliminated in the comparisons described in this paper. The frequencies of the two standards under consideration are compared by obtaining direct beats between them. The method is of course only applicable when the frequencies are very nearly equal; or when one is a simple multiple of the other, in which case the beats are obtained between the appropriate harmonics.

(2) NATURE OF THE EMISSIONS, AND METHODS OF MEASUREMENT.

A radio-frequency wave of any convenient value is modulated at a frequency of 1 000 cycles per sec. by a supply obtained from a standard tuning fork. A modulation frequency of 1 000 cycles per sec. is chosen because it is known that a large number of organizations have adopted this as their basic frequency. It is in general use as the fundamental frequency of "multivibrators," by which a large range of radio frequencies can be generated as integral multiples of the fundamental frequency. The emission is made from a sufficiently powerful station, and the modulation frequency is received at the distant stations and compared with the local standards. This comparison consists of two distinct measurements: (a) The measurement of the frequency-difference, Δf , between the received signal and the local frequency standard. (b) The measurement of the frequency of the local standard in terms of the mean solar second.

(a) Measurement of the Frequency-Difference, Δf .

Where the local standard is a tuning fork vibrating at 1 000 cycles per sec., beats are obtained directly between the received signal and an output from the fork. The number of beats per second, Δf , can be measured either aurally by means of a telephone receiver coupled to the two supplies, or visibly by means of a vibration galvanometer or cathode-ray oscillograph; or, most accurately,

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† S. JIMBO: "An International Comparison of Frequency by means of a Luminous Quartz Resonator," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 1930.

by feeding the two supplies to an amplifier and using the rectified output of this to operate a marker on an automatic tape recorder.

The local standard may consist of a quartz oscillator operating at a frequency which is a multiple of 1 000 cycles per sec. It is then possible either to de-multiply the frequency of the local standard and to count the beats at 1 000 cycles per sec.; or alternatively to multiply the frequency of the received signal to that of the quartz oscillator and count the beats at the higher frequency.

Expressed as a fraction, the accuracy of measuring the frequency-difference is given by the expression $\Delta f \times \Delta t/t$, where t is the time occupied in measuring Δf , and Δt is the error in the measurement of t .

Δt does not depend on the timing mechanism alone; it is also a function of Δf . As the beat becomes slower the accuracy of timing the beat decreases; and it is usually found that for values of Δf less than 0.02 cycle per sec. Δt increases by about the same proportion as Δf decreases.

Under good conditions, with $\Delta f = 0.02$ cycle per sec., Δt is about 0.2 sec.; and, if one beat is timed, $t = 50$ sec. The accuracy is therefore 8 parts in 10^5 . This is the accuracy of the measurement of a frequency-difference between two frequencies of very nearly 1 000 cycles per sec., so that the accuracy of the frequency comparison is 8 parts in 10^8 . If the comparisons are carried out at a higher frequency the accuracy of the frequency comparison is proportionately increased.

An advantage in employing a low frequency such as 1 000 cycles per sec. as the comparison standard is that it can be supplied to the emitting station from a considerable distance, enabling it to be generated by a standard oscillator maintained under steady conditions of operation at a distant laboratory.

(b) *Determination of the Frequency of the Local Standard.*

In order to measure the frequency of the local standard in terms of the mean solar second it was necessary to integrate the oscillations over a period of time measured by means of the Observatory time signals. A phonic motor was employed. This was driven by a 1 000-cycle per sec. supply obtained from the standard fork and was provided with a contact which was made once for a definite number of oscillations. The contact operated a pen on a chronograph, on which were also recorded the signals from the Observatory. The number of phonic-wheel contacts gave the total number of oscillations, and from the time signals the total time was measured, usually with an accuracy of about 0.01 sec. To obtain an accuracy of 1 part in 10^7 in the frequency measurement it was therefore necessary to extend the observations over a period of about 24 hours.

The time signals themselves are subject to errors which do not usually exceed ± 4 parts in 10^7 . In the experiments described in this paper it is not known in every case what signals were used for determining the frequency of the standard. The results have therefore not in general been corrected for the signal errors. The errors of the time signals used by the Institut Radiotechniczny were large, and the corrections have been applied to the results of measurements made at that laboratory.

(c) *Frequency of the Received Signal.*

The knowledge of the absolute frequency of the local standard combined with that of the frequency-difference gives two possible values for the frequency of the received signal depending on the algebraic sign of Δf , which may be difficult to determine when Δf is small. In practice the emitted frequency was usually known with sufficient accuracy to avoid ambiguity in the results; but in the later comparisons the frequency of emission was changed by a small amount for a period after the main emission, to enable the sign of the frequency-difference to be determined.

(3) RESULTS OF THE COMPARISONS.

Up to the present time eleven comparisons have been carried out, including those of an experimental nature. Only one of the earlier comparisons is described in this paper, showing the accuracy attained at that time. The results of the last two comparisons, in which a much greater accuracy was obtained, are also included. All of these three emissions took place from the Daventry 5XX station working on a carrier frequency of 193 kilocycles per sec. (wavelength 1 554 m).

(a) *Emission of 30th September, 1931, 10.00–11.00 G.M.T.*

The modulation was obtained from a tuning fork installed in the laboratories of the British Broadcasting Corporation at Tatsfield, and was sent to Daventry by landline. The fork was contained in a temperature-controlled oven, but the control was not very satisfactory. The results of the measurements are given in Fig. 1. It is seen that the agreement obtained is about 2 parts in 10^6 . Observations were also made at the Institut Radiotechniczny, Warsaw, but, owing to the poor reception, measurements were only possible for a period of 8 minutes. The value obtained there was 999.952 cycles per sec.

(b) *Emission of 29th–30th June, 1932, 23.55–01.45 G.M.T.*

The modulation for this emission was obtained from the standard fork at the National Physical Laboratory and was sent to Daventry by landline. This fork, which is described in detail in another paper,* is maintained in continuous vibration, and its frequency is usually known at any time with an accuracy of ± 1.5 parts in 10^7 . Arrangements were provided for making small changes in the frequency of the fork. After the modulation had been emitted continuously for 90 minutes the frequency was changed by -2.5 parts in 10^6 and the emission continued for another 15 minutes. To verify the frequency stability of the fork during the emission it was compared with a quartz oscillator having a frequency of 20 000 cycles per sec. The frequency-difference between the quartz oscillator and the 20th harmonic of the fork averaged over 10-minute intervals remained constant to 1 part in 10^8 , although there were departures from this mean value of as much as 6 parts in 10^8 in an extreme case. Previous experience had shown that the quartz oscillator is not usually subject to variations exceeding 1 part in 10^8 during hourly periods. The

* D. W. DYE and L. ESSEN: "The Valve Maintained Tuning Fork as a Primary Standard of Frequency," *Proceedings of the Royal Society, A*, 1934, vol. 143, p. 285.

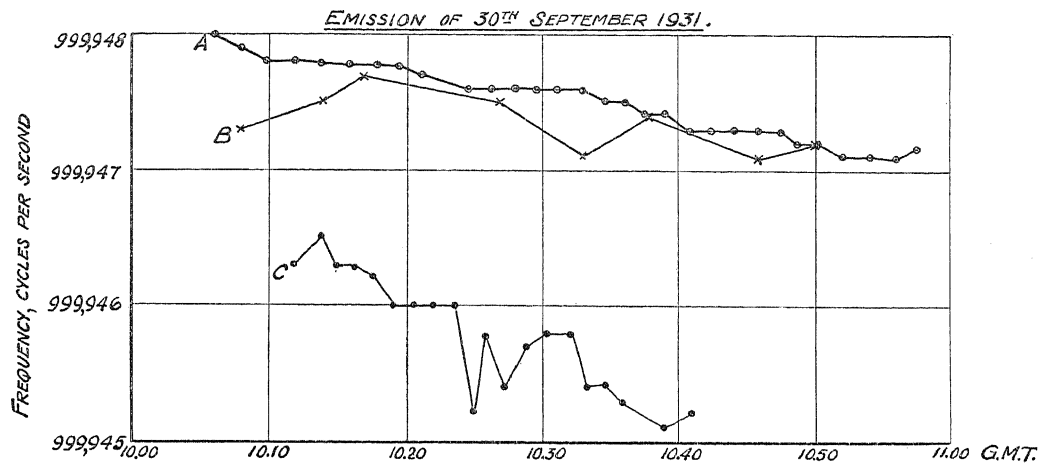


FIG. 1.

A. National Physical Laboratory, Teddington.
 B. Laboratoire National de Radioélectricité, Paris.
 C. Union Internationale de Radiodiffusion, Brussels.

results of the measurements made at the various national laboratories are given in Table 1. As there was no frequency drift the mean values obtained, and the maximum deviations from these values, are given.

located nearly 100 miles away, the control being effected through a landline and amplifiers. An experiment was made during the emission of the 21st December, 1932, to determine whether there was a measurable difference

TABLE 1.

Results obtained during emission of 29th–30th June, 1932.

Laboratory	Mean frequency	Maximum deviation from the mean
	cycles per sec.	cycles per sec.
National Physical Laboratory	1 000·0001	0·00006
Physikalisch-Technische Reichsanstalt, Berlin .. .	1 000·0002	0·0003
Laboratoire National de Radioélectricité, Paris .. .	1 000·0001	0·0003
Institut Radiotechniczny, Warsaw .. .	999·9997	0·0004

(c) *Emission of 21st December, 1932, 02.00–03.30 G.M.T.*

The modulation was again obtained from the National Physical Laboratory standard fork. The results are embodied in Table 2.

TABLE 2.

Results obtained during emission of 21st December, 1932.

Laboratory	Frequency
	cycles per sec.
National Physical Laboratory ..	999·9999
Physikalisch-Technische Reichsanstalt, Berlin	999·9998
Institut Radiotechniczny, Warsaw ..	999·9999

(4) EXPERIMENT TO TEST THE ACCURACY OF THE FREQUENCY CONTROL BY THE STANDARD OSCILLATOR.

The frequency of modulation of the aerial current of the emissions from Daventry was controlled by a standard

between the frequency of emission and that of the standard. A multivibrator was controlled directly by the standard tuning fork at 1 000 cycles per sec. It was arranged to generate the 20th harmonic, and the difference in frequency between this and the frequency of a quartz-ring oscillator of 20 kilocycles per sec. was measured. In the same way measurements were also made of the frequency-difference between the 20th harmonic of the note received from Daventry and the same quartz oscillator. The results of the first set of measurements fall on a smooth curve (Fig. 2) within a few parts in 10^9 , and the accuracy of the individual observations is estimated at ± 1 part in 10^9 . The received signal was slightly disturbed, which decreased the accuracy of the frequency comparison. It was possible, however, to make a number of observations with an accuracy believed to be ± 1.5 parts in 10^8 , and these are shown as small circles on the curve. It is noteworthy that whenever it was possible to measure the signal with an accuracy of ± 1.5 parts in 10^8 it was found to agree with the tuning-fork frequency within that limit. If the results are averaged over the whole of the time during

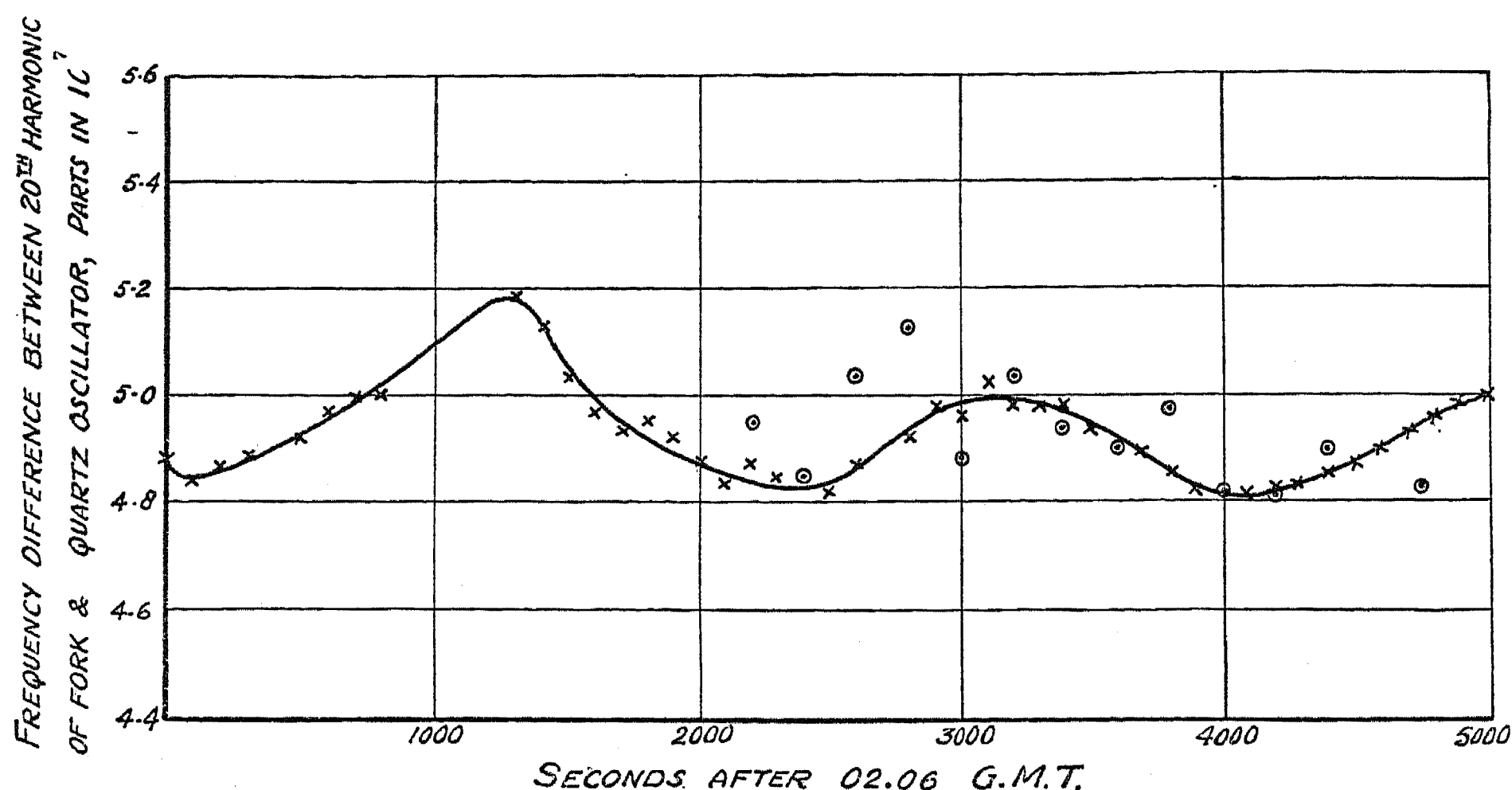


FIG. 2.

which observations on the received signal were made it is found that the frequencies agree to 1 part in 10^9 .

It was concluded that under the conditions of the experiment the tuning fork controls the frequency of modulation emitted by the aerial with an accuracy of at least 2 parts in 10^8 .

(5) CONCLUSIONS.

Comparisons of primary standards of frequency by means of modulation emissions can be made with an accuracy of 2 parts in 10^8 .

By means of such measurements the fundamental standards in use in England, France, Germany, and Poland, have been shown to agree to ± 1 part in 10^7 , which is the order of accuracy with which absolute

determinations of frequency in terms of the mean solar second can be made.

(6) ACKNOWLEDGMENTS.

The measurements made at the National Physical Laboratory were carried out for the Radio Research Board. The work was only made possible by the co-operation of the various other standardizing laboratories, which was secured through the Union Radio-Scientifique Internationale, and by that of the British Broadcasting Corporation, who made themselves entirely responsible for the emissions.

Particular acknowledgment is due to the late Dr. D. W. Dye, F.R.S., who initiated these comparisons, and to Dr. E. H. Rayner, who organized the emissions subsequent to Dr. Dye's death.

THE RECEPTION OF WIRELESS SIGNALS IN NAVAL SHIPS.

By W. F. RAWLINSON, D.Sc., Associate Member.

(Paper first received 9th December, 1933, and in final form 11th May, 1934; read before the WIRELESS SECTION 7th March, 1934.)

SUMMARY.

The paper discusses problems encountered in the reception of wireless signals in naval ships. Certain features of apparatus which has been developed are described.

The paper is divided into four principal sections:—

- (1) Aerials and cable systems, in which the problem of connecting the aerial to the receiver is examined.
- (2) General conditions to be fulfilled by naval receivers. This section contains a discussion of the problem of selectivity from the naval point of view.
- (3) Brief description of receivers.
- (4) Power supplies utilizing batteries and alternating current.

INTRODUCTION.

The main object of the paper is to discuss the particular difficulties encountered in the reception of wireless signals in naval ships and to refer to apparatus which has been developed to overcome these difficulties and fulfil the stringent requirements necessary for service under seagoing conditions.

Any modern receiving system can be divided into three major portions: (a) The aerial system. (b) The receiver. (c) Receiver power supplies. Each of these involves special problems, when considered from the naval point of view.

The paper is therefore divided into four principal sections: (1) Aerials and cables. (2) General conditions to be fulfilled by naval receivers. (3) Description of receivers. (4) Receiver power supplies.

(1) AERIALS AND CABLES.

In a man-of-war the choice of receiving aerials is exceedingly limited. There are, in general, one fairly high mast and either a second smaller mast or some form of control structure. To these, all aerials for both transmitting and receiving must be attached. Between these two high points the ship's main aerial is slung, and the remainder of the aerials are run up to one or other of them. The down leads must keep fairly close to the mast or superstructure to avoid fouling guns, boats, or derricks. A receiving aerial may therefore be anything from the ship's main aerial with a capacitance of $0.003 \mu\text{F}$ to a short single wire (say 15 ft. long) with a capacitance of about $0.0001 \mu\text{F}$.

In large ships the central receiving room is placed well down below armour, and the distance between the central receiving room and the foot of the aerials may be up to 100 ft. The aerial itself therefore terminates in a deck insulator and junction box, from which a special paper-and-air insulated cable is run to the receiver in the office.*

* G. SHEARING: *Journal I.E.E.*, 1934, vol. 74, p. 14.

This aerial and cable system has a large influence on the design of the input circuits for naval receivers, and on the signal strengths obtainable. The following calculation shows the properties which a cable should possess if it is to form a satisfactory coupling between aerial and receiver. For the case of low and medium frequencies, the cable may be considered to behave as a capacitance C in parallel with a conductance G (representing its dielectric and leakage losses), in parallel with the aerial capacitance C_1 . Consider the theoretical circuit shown in Fig. 1(a), in which the combination of C , C_1 , and G , in parallel is tuned by an inductance L which has resistance r . Let a high-frequency e.m.f. Ee^{jpt} be applied between the points A and B. If Z is the impedance between the points K and L, then

$$\frac{1}{Z} = G + jpC + jpC_1 \quad (1)$$

$$Z = \frac{1}{G + jp(C + C_1)} = \frac{G - jp(C + C_1)}{G^2 + p^2(C + C_1)^2} \quad (2)$$

Hence if \bar{Z} is the impedance between the points A and B,

$$\begin{aligned} \bar{Z} &= jpL + r + Z \\ &= r + \frac{G}{G^2 + p^2(C + C_1)^2} + jpL - \frac{jp(C + C_1)}{G^2 + p^2(C + C_1)^2} \end{aligned} \quad (3)$$

Now, for any normal cable, $G^2 \ll p^2(C + C_1)^2$

$$\therefore \bar{Z} \doteq r + \frac{G}{p^2(C + C_1)^2} + jpL + \frac{1}{jp(C + C_1)} \quad (4)$$

The current i through the inductance L is given by

$$i = \frac{E}{\left[r + \frac{G}{p^2(C + C_1)^2} \right] + jpL + \frac{1}{jp(C + C_1)}} \quad (5)$$

The current becomes a maximum and the circuit is in tune when

$$pL = \frac{1}{p(C + C_1)}$$

and

$$i_{\max.} = \frac{E}{r + \frac{G}{p^2(C + C_1)^2}}$$

The current i_1 through the capacitance C_1 is approximately equal to

$$\frac{C_1}{C + C_1} i$$

since $G \ll p(C + C_1)$.

Hence
$$i_{1max.} = \frac{\frac{C_1}{C + C_1} E}{r + \frac{G}{p^2(C + C_1)^2}} \quad \dots \quad (6)$$

Using the reciprocal theorem that in any network the source of e.m.f. and the ammeter can be interchanged without altering the ammeter reading, it follows that for the circuit of Fig. 1(b) the current $i_{1max.}$ through the inductance L is given by (6) above. This circuit corresponds to that of the aerial, cable, and tuning inductance in a receiver, when a wireless wave induces an

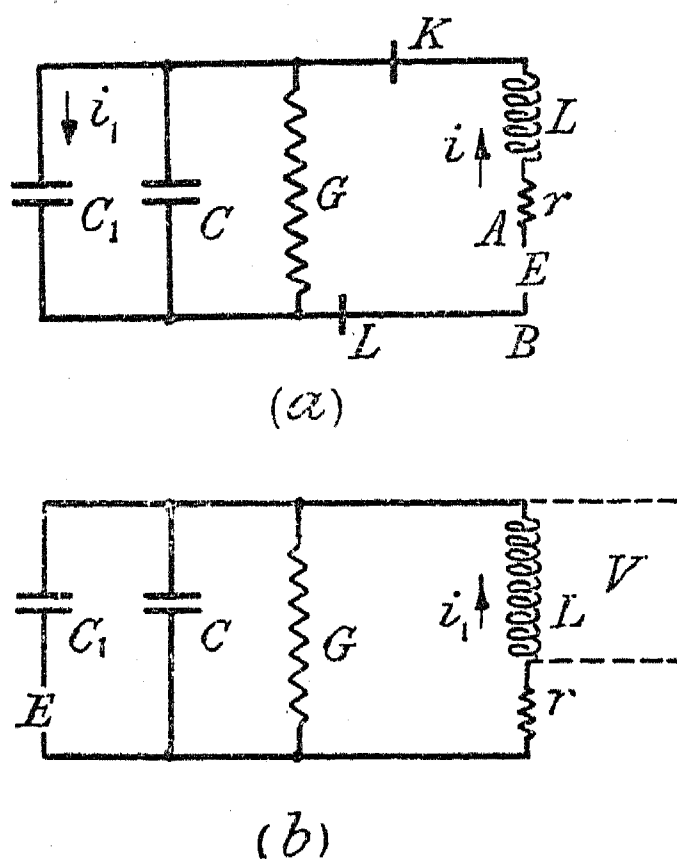


FIG. 1.

e.m.f. E in the aerial. The amplitude of the voltage V across the inductance L is given by

$$V = \frac{pL \frac{C_1}{C + C_1} E}{r + \frac{G}{p^2(C + C_1)^2}} = \frac{\frac{C_1}{C + C_1} E}{\frac{r}{pL} + \frac{G}{p(C + C_1)}} = \frac{\frac{C_1}{C + C_1} E}{\frac{r}{pL} + \frac{G}{pC} \frac{C}{C + C_1}} \quad \dots \quad (7)$$

If both C and G were zero, i.e. if no cable was fitted,

$$V' = \frac{E/r'}{pL'} \quad \dots \quad (8)$$

where r' and pL' are the resistance and inductance of the coil which is required to tune C_1 alone to the given frequency.

Now $r/(pL)$ is the power factor of the inductance, and $G/(pC)$ that of the cable, whilst $r'/(pL')$ is the power factor of the larger inductance required to tune C_1 alone. For the type of inductances which can be used in practice, $r/(pL)$ and $r'/(pL')$ will be of the same order of magnitude, i.e. about 0.01. Equations (7) and (8) therefore show that the effect of the cable is to reduce the voltage developed across the inductance in two ways: (1) It reduces the effective voltage in the aerial, in the ratio $C_1/(C + C_1)$. (2) It adds to the power factor of

the inductance, a quantity roughly equal to the power factor of the cable.

The best cable will therefore be that for which both C and $G/(pC)$ are least, i.e. the cable with the least capacitance per unit length and the smallest power factor.

In practice the circuit of Fig. 1(b) would be tuned by using a fixed value of L and a series capacitance C' . If pL' is written for $[pL - 1/(pC')]$, equation (6) still gives the value of $i_{1max.}$, but p^2 is now determined by the relation

$$pL' = \frac{1}{p(C + C_1)}$$

Equation (7) for V is then replaced by

$$V = \frac{\frac{C_1}{C + C_1} E}{\frac{r}{pL} + \frac{G}{p(C + C_1)} \frac{L'}{L}} \quad \dots \quad (9)$$

It might therefore appear that the effect of the power factor of the cable could be made negligible by making C' very small and L very large, and thus obtaining a small value for L'/L . Tests show, however, that, in the case of a cable with a bad power factor, the inductance L has to be made so large that the power factor $r/(pL)$ is increased more rapidly than the effective power factor of the cable is decreased, and the circuit having a very large value of L is actually worse than that with a small value.

When the reception of high frequencies is examined the aerial and cable system present even greater difficulties, and the cable must be treated as a transmission line or feeder. In the case of a shore station working on a fixed frequency, it is possible to use a tuned aerial and to render the feeder system non-reflective by means of suitable transformers between aerial and feeder, and between feeder and receiver. The feeder system then has no effect on the tuning of either the aerial or the receiver, and the question of losses is the only one to be considered. On board ship, however, this ideal solution of the cable problem is impossible. The aerial itself cannot be tuned, the frequency to be received is not fixed, the length of cable which may connect the aerial to the receiver varies over wide limits from ship to ship, and the fitting of any form of tuneable circuit between aerial and cable is out of the question. Under these conditions the best cable will clearly be that for which the velocity of propagation of electromagnetic waves is highest, for serious difficulties in tuning will not arise until the cable becomes approximately one quarter-wave-length long. Now the velocity of propagation of electromagnetic waves is given by (Velocity of light)/ $\sqrt{(\text{Dielectric constant})}$; hence the best cable will be that for which the dielectric constant is least.

To the electrical requirements must be added others such as permissible diameter, mechanical strength, ability to bend into a curve of small radius, etc. The final compromise is therefore a cable having the following constants: Capacitance, 0.001 μF per 100 ft.; power factor, 1.2 per cent at 100 kilocycles per sec.; dielectric constant, 1.5 (approx.).

(2) GENERAL CONDITIONS TO BE FULFILLED BY NAVAL RECEIVERS.

The ship's main wireless office consists of a single room, which is completely silent-lined and surrounded by a steel shell. So far as screening from disturbances external to the ship or direct pick-up of unwanted signals on the receivers is concerned, the office may be said to be virtually perfect. This must not be taken to mean that interference within the office is negligible. In actual practice the noise level is usually high owing to sparking and radiation from ventilation fans, light wiring, and other electrical machinery in the ship. Light wiring, control leads for transmitters, buzzer leads, etc., must of necessity enter the office, and, as is well known, any lead which penetrates a Faraday cage is liable to bring in interference, especially on high frequencies. Although

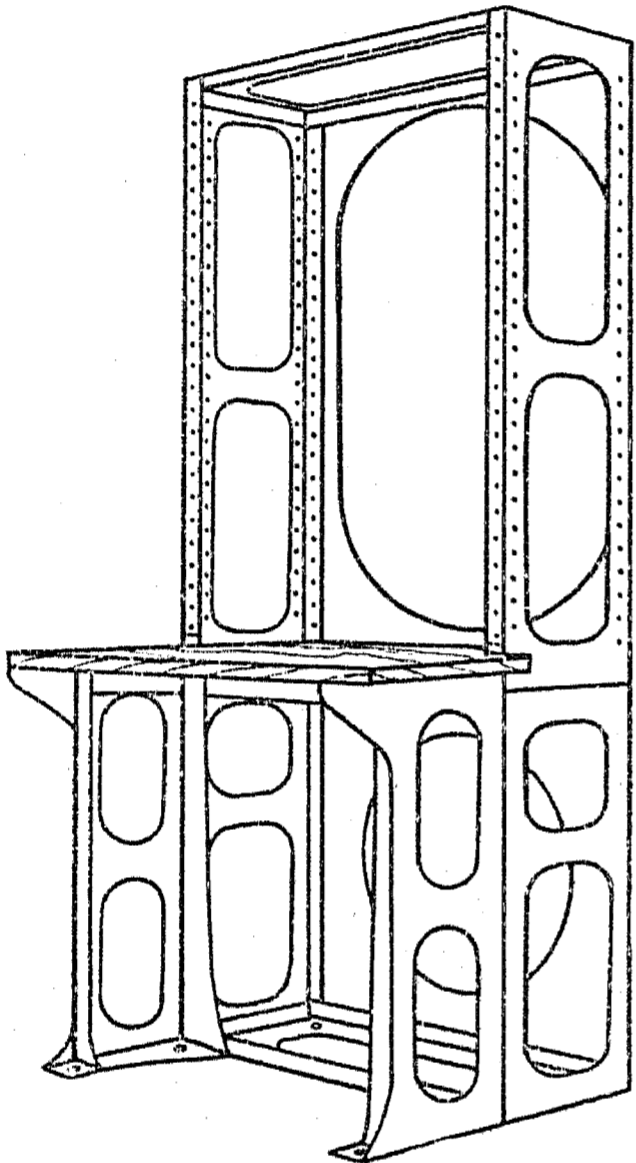


FIG. 2.—Rack for mounting receivers.

this interference can often be considerably reduced by fitting radio-frequency filter circuits into the output leads of small machines, and into buzzer and control leads just before they enter the office, it is still necessary to screen each receiver separately. The receivers are therefore built up in the form of an aluminium face-plate carrying all components, fitting into a sheet-metal box which is earthed.

Robustness of design is essential in all naval receivers. They must continue to work for years with an absolute minimum of attention under temperatures varying from tropical heat to arctic cold, and in a salt-water-laden atmosphere; hence the insistence on the use of best-quality components. Further, the receivers must work for 24 hours per day, during which time control handles are being continually adjusted.

Again, the whole office, and in consequence the receivers themselves, are subjected at times to tremendous vibration, if the ship is travelling at full speed, whilst in action the apparatus must stand up to the concussion from the guns or from shell bursts on the ship. This presents problems due to microphony of the

valves; the detector valves of all naval receivers have to be separately sprung. It also brings into prominence the mounting of the receivers. Receivers were for many years screwed to the bulkheads, but this never gave entire satisfaction, for in the smaller classes of ships they were always liable to be torn down by the concussion from gunfire. In modern ships, therefore, a system of rack mounting has been adopted. The racks are made up of aluminium alloy castings bolted together, and are themselves bolted to the deck. Connections to the bulkhead or roof of the office are made only by means of flexible cables. The castings are designed to withstand the strains imposed upon them owing to whip in the deck. A typical rack is illustrated in Fig. 2. The upper part of the rack holds the receivers; the lower part at the rear holds such apparatus as cushioning units for supply leads, whilst the lower front part supports the operator's table.

As in the design of all other types of receivers, the valves to be used play a large part in the decision of circuit details. Since the introduction of broadcasting, valve manufacturers have made improvement after improvement in their products and have put upon the market a very large number of valves of special types with remarkable characteristics. To obtain the best results with a minimum number of stages it is necessary to use the best type of valve for each stage and to design the circuits to fit the valve characteristics. The use of a large number of special types of valves is not possible under Service conditions, since ships must operate in all parts of the world and depend for their spares and replacements on the valves which they themselves carry or on stocks held at various dockyards. Further, receivers must be standardized for a period of several years and there is as yet no sign of finality in valve characteristics. Three types of valves have therefore been adopted for naval use: a screen-grid valve for high-frequency amplification, a general-purpose valve for detection and note magnification, and a power valve for use as an oscillator and for any other purpose for which a larger output is required than can be handled by the general-purpose valve. The specifications of these valves were so drafted as to accept valves which were typical of the best in their classes at the time, and it was hoped by this means to ensure a steady supply of valves without having resort to special manufacture. This hope has not been fulfilled. Valves adopted a few years ago are now obsolescent and are apparently kept alive by Service demands. The question of valve supplies is a very serious one, for it is obviously impossible to scrap receivers every few years or even to modify them, and it is equally impossible to design receivers so that they can be used with valves of entirely different characteristics. Even with present valve specifications such wide tolerances must be given as to make repetition performance of receivers difficult.

Apart from this difficulty in maintaining supplies of valves, the standardization of only a few types sets a limit to the circuits which can be used. The details of all naval receivers must be considered from this standpoint. From the point of view of life and liability to accidental damage the valve is also the weakest link in the chain, and all receivers are so designed that valves

can easily be taken out and replaced from the front of the model. This of necessity puts a certain limit on the lay-out of the various components in the receivers, but it is essential, since space is not available in the offices for access to the back of the models.

The design of receivers for naval ships is greatly influenced by technical requirements not generally met with in shore receiving stations. In service at sea it is necessary to receive several signals simultaneously within the frequency range 15–23 000 kilocycles per sec. Whilst these signals in general fall into well-defined bands, their frequencies cannot be fixed; they may in fact have to be changed at any time to allow for local conditions or jamming. Again, the number of receivers which can be fitted is limited by considerations of weight, space, and the number of operators available. It is therefore impossible to provide one receiver for each line of reception, or to develop an ideal receiver for any one particular purpose. Further, it is essential that as far as possible the same types of receivers shall be used in all classes of ships. This results in very wide frequency ranges being covered by each receiver, the least being 10 to 1 and the greatest 30 to 1 for normal models, whilst for one particular receiver it is 1 333 to 1. Such wide ranges give rise to many serious difficulties.

One of the fundamental points in all types of receiver designs is the question of selectivity. There appears to be no definition of this term which will cover all cases. Moreover, many of the definitions which have been framed relate to the separation of stations working on neighbouring telephony channels and of comparable field strength. Selectivity in this sense has little meaning in naval practice. Naval receivers are designed primarily for the reception of morse signals, either continuous-wave (C.W.) or interrupted continuous-wave (I.C.W.), and such matters as side-band cutting, tone correction, or fidelity of reproduction, are of very minor importance. The problem of selectivity in ships at sea is something entirely different. It is the problem of receiving a very weak C.W. or I.C.W. signal in the presence of a much more powerful signal transmitted by the receiving ship, a near-by ship, or some powerful coast station; the two signals being, in general, fairly well separated in frequency. For this type of interference the so-called highly selective receiver, embodying a single tuned circuit of very low decrement, does not prove in practice to be the receiver of greatest selectivity. To illustrate this, consider two magnetically-coupled circuits such as those shown in Fig. 3, and let an e.m.f. $E \cos pt$ of frequency f (where $p = 2\pi f$) be applied in circuit I.

Putting

$$X_1 = pL_1 - \frac{1}{pC_1} \quad \dots \quad (10)$$

and

$$X_2 = pL_2 - \frac{1}{pC_2} \quad \dots \quad (11)$$

it can be shown that the amplitude of the current i_2 is given by

$$|i_2| = \frac{pME}{\sqrt{(R_2^2 + X_2^2)} \sqrt{\left[\left(R_1 + \frac{p^2 M^2}{R_2^2 + X_2^2} R_2 \right)^2 + \left(X_1 - \frac{p^2 M^2}{R_2^2 + X_2^2} X_2 \right)^2 \right]}} \quad \dots \quad (12)$$

If p_0 is the value of p for which

$$X_1 = X_2 = 0 \quad \dots \quad (13)$$

then, provided that M is chosen so that $p_0^2 M^2 \leq R_1 R_2$ (i.e. the coupling is less than optimum), $|i_2|$ becomes a maximum for this value of p_0 , and

$$|i_2|_{\max} = \frac{p_0 M E}{R_1 R_2 + p_0^2 M^2} \quad \dots \quad (14)$$

The amplitude of the voltage V_2 across the condenser C_2 is given by $|V_2| = \frac{|i_2|}{pC_2}$.

$$\text{Hence} \quad |V_2|_{\max} = \frac{\frac{M}{C_2} E}{R_1 R_2 + p_0^2 M^2} \quad \dots \quad (15)$$

For any other frequency p , sufficiently far removed

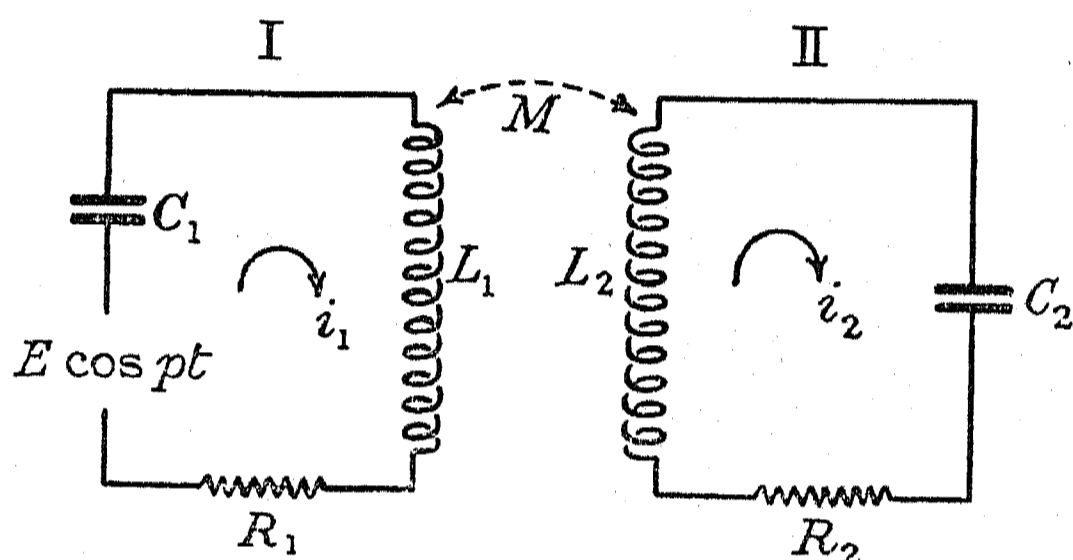


FIG. 3.

from p_0 for R_2^2 to become negligible compared with X_2^2 and R_1^2 negligible compared with X_1^2 ,

$$|i_2| = \frac{pME}{X_2(X_1 - p^2 M^2/X_2)} = \frac{pME}{X_1 X_2 - p^2 M^2} \quad \dots \quad (16)$$

and

$$|V_2| = \frac{\frac{M}{C_2} E}{X_1 X_2 - p^2 M^2} \quad \dots \quad (17)$$

Hence, if $|V_2|_{\max}$ is the wanted signal to which the circuits are tuned and $|V_2|$ is the interfering signal of different frequency,

$$\frac{|V_2|}{|V_2|_{\max}} = \frac{R_1 R_2 + p_0^2 M^2}{X_1 X_2 - p^2 M^2} \quad \dots \quad (18)$$

To simplify formula (18), assume $R_1 = R_2$ and $X_1 = X_2$. Then

$$\begin{aligned} \frac{|V_2|}{|V_2|_{\max}} &= \frac{R_1^2 + p_0^2 M^2}{(X_1 + pM)(X_1 - pM)} \\ &= \frac{R_1^2 + p_0^2 M^2}{\left[pL_1(1+K) - \frac{1}{pC_1} \right] \left[pL_1(1-K) - \frac{1}{pC_1} \right]} \quad (19) \end{aligned}$$

where K = coefficient of coupling between L_1 and $L_2 = M/L_1$.

It has already been assumed that $p_0^2 M^2 < R_1 R_2$.

Hence

$$M^2 < \frac{R_1^2}{p_0^2}$$

$$\frac{M^2}{L_1^2} < \frac{R_1^2}{p_0^2 L_1^2}$$

$$K^2 < \frac{1}{m_1^2}$$

where $m_1 = p_0 L_1 / R_1$ = magnification of the coil, and is large. Hence, for the assumed condition $X_1^2 \gg R_1^2$, we can simplify (19) still further without any large error and write

$$\frac{|V_2|}{|V_2|_{max.}} = \frac{R_1^2(1+x^2)}{X_1^2} \quad (20)$$

where x^2 is a constant, is always less than unity and diminishes as the coupling is reduced.

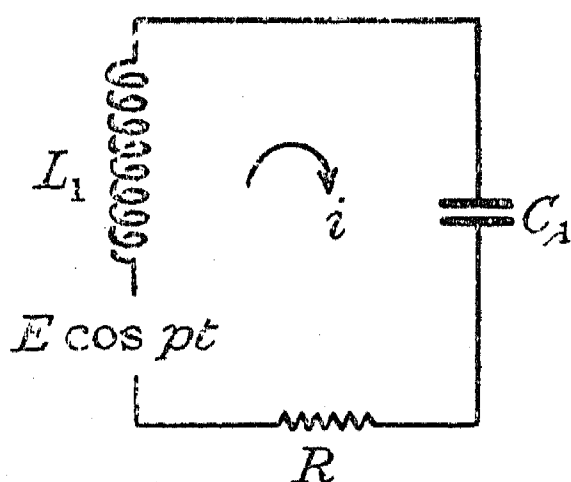


FIG. 4.

For values of p such that $p \ll p_0$,

$$\begin{aligned} \frac{|V_2|}{|V_2|_{max.}} &\doteq \frac{R_1^2(1+x^2)}{1} \\ &\doteq \frac{p^2 C_1^2}{p^2 C_1^2 R_1^2 (1+x^2)} \\ &\doteq \frac{p^2}{p_0^2} \frac{p_0^2 C_1^2 R_1^2 (1+x^2)}{p_0^2 C_1^2 R_1^2 (1+x^2)} \\ &\doteq \frac{p^2}{p_0^2} \frac{R_1^2}{L_1^2 p_0^2} (1+x^2) \\ &\doteq \frac{p^2 (1+x^2)}{p_0^2 m_1^2} \quad (21) \end{aligned}$$

For values of p such that $p \gg p_0$,

$$\begin{aligned} \frac{|V_2|}{|V_2|_{max.}} &\doteq \frac{R_1^2(1+x^2)}{p^2 L_1^2} \\ &\doteq \frac{p_0^2 (1+x^2)}{p^2 m_1^2} \quad (22) \end{aligned}$$

Now consider a single tuned circuit such as that shown in Fig. 4, having the same values of L_1 and C_1 but a resistance R different from R_1 (R will ultimately be assumed to be much less than R_1).

For this circuit,

$$|i| = \frac{E}{\sqrt{R^2 + X_1^2}} \quad (23)$$

In this case the amplitude of i becomes a maximum for the same frequency p_0 such that

$$X_1 = 0$$

and

$$|i|_{max.} = \frac{E}{R} \quad (24)$$

The amplitude of the voltage V across the condenser C_1 is again given by

$$|V| = \frac{|i|}{pC_1}$$

$$\text{Hence } |V|_{max.} = \frac{\frac{E}{R}}{p_0 C_1} \quad (25)$$

For any frequency p so far removed from p_0 that R^2 is negligible compared with X_1^2 ,

$$|V| = \frac{E}{pC_1 X_1}$$

$$\text{Hence } \frac{|V|}{|V|_{max.}} = \frac{p_0 R}{p X_1} \quad (26)$$

For values of p such that $p \ll p_0$,

$$\begin{aligned} \frac{|V|}{|V|_{max.}} &\doteq \frac{p_0 R}{1} \\ &\doteq \frac{p_0 R}{p C_1} \\ &\doteq p_0 C_1 R \\ &\doteq \frac{R}{p_0 L_1} \\ &\doteq \frac{1}{m} \quad (27) \end{aligned}$$

where m = magnification of this single coil, and is large.

For values of p such that $p \gg p_0$,

$$\begin{aligned} \frac{|V|}{|V|_{max.}} &\doteq \frac{p_0 R}{p^2 L_1} \\ &\doteq \frac{p_0^2 R}{p^2 p_0 L_1} \\ &\doteq \frac{p_0^2}{p^2} \frac{1}{m} \quad (28) \end{aligned}$$

Comparing formula (21) and formula (27) it is seen that, for values of $p \ll p_0$, $|V_2|/|V_2|_{max.}$ will always become less than $|V|/|V|_{max.}$ whatever the values of m_1 and m ; that is, for frequencies sufficiently well below the resonant frequency, two loosely-coupled circuits—however low their magnification—will be more selective than a single circuit however high its magnification may be.

Comparing formulæ (22) and (28), it is seen that, where $p \gg p_0$, $|V_2|/|V_2|_{max.}$ will become less than $|V|/|V|_{max.}$ only if

$$\frac{(1+x^2)}{m_1^2} < \frac{1}{m}$$

i.e. only if $m_1^2 > m(1+x^2)$.

This condition, however, is fairly easily obtained with ordinary circuits. The constant α is at our disposal and is always less than unity; and in practical cases when high selectivity is required the coupling is always very loose, so that α is very small compared with unity. Under this condition two ordinarily good circuits with a magnification a little greater than 100 will be better than a single circuit of magnification 10 000 for frequencies sufficiently higher than the resonance frequency. The figure of 10 000 is chosen for comparison since it is the value given in Radio Research Board Special Report No. 12 as the order of the maximum magnification likely to be obtained for a single circuit with retro-action. (The actual measured values given in this Report were 10 000/3 to 10 000/8, and for either of these values two very ordinary circuits would fulfil the conditions.)

In practice, therefore, when very high selectivity is required against powerful signals of frequencies far removed from the frequency it is desired to receive, it is better to use two fairly loosely-coupled circuits, than to attempt to design and operate a single circuit of the lowest decrement which can be obtained in practice by means of reaction. In addition the coupled circuits are followed by tuned intervalve stages which behave theoretically as further circuits with zero coupling, thus adding still more to the selectivity. Naval low-frequency and medium-frequency receivers are therefore designed in accordance with this principle.

The separation of a required station from a station of comparable strength on a near-by frequency is accomplished by the use of a separate heterodyne and low-frequency note selectors for low- and medium-frequency continuous waves. With a separate heterodyne the two beat notes have different frequencies, and the beat note from the required station can be made exactly that which will be accepted and amplified by the note selectors. I.C.W. is only used on the higher frequencies, and here the separation of the stations is sufficiently great to make the radio-frequency selectivity alone sufficient.

A further point of great importance in the design of receivers is the fact that under certain conditions a number of aerials may be put out of action. In the worst case it may be necessary to use all receivers on a single aerial. There is no ideal solution to this problem and the only practical solution appears to be to make it possible to fit, when necessary, a screen-grid valve as an isolating valve in front of each receiver, and to resistance-couple the aerial to this valve. With such an arrangement the aerial is rendered practically non-oscillatory and is virtually decoupled from the tuned circuits of the receiver. Connecting several receivers to one aerial results merely in placing the various resistances in parallel between aerial and earth. The tuning of the receiver circuits is then uninfluenced by the aerial in use, but it will be obvious that this method of connecting the aerial may at times introduce troubles due to cross-modulation, and the simple circuit has of necessity been somewhat modified.

Finally, there are a few isolated cases where it is not possible to erect an aerial at all, and a special non-directional receiver has been developed using two crossed frame coils, which embodies some interesting points.

DESCRIPTION OF RECEIVERS.

Short-Wave Receiver.

This receiver covers the frequency range 1 500–23 000 kilocycles per sec., thus providing for long-range work in the band 6 000–23 000 kilocycles per sec. and short-range working in the band 1 500–6 000 kilocycles per sec. Its circuit diagram is shown in Fig. 5.

The receiver has two high-frequency stages in separate screened compartments, a detector with reaction, and two stages of note magnification. At frequencies above 5 000 kilocycles per sec. one high-frequency stage with screen-grid valve is employed. At lower frequencies either one or two high-frequency stages may be used. One or both stages of note magnification can be cut out if desired.

The aerial circuit of the receiver is untuned, and a plug and flexible connection allows the aerial to be connected to the grid of either the first or the second high-frequency valve. The resistance between aerial and earth is 1 000 ohms and is protected by a lightning arrestor of the gas-gap type. Inserting the aerial plug into the jack of the second high-frequency stage disconnects the tuned anode-circuit of the first high-frequency valve. The aerial circuit is therefore untuned in each case. As previously mentioned, this arrangement has been adopted to allow the use of multiple reception. In addition, it has the advantage of reducing the radiation from the aerial caused by the oscillating detector circuit.

Both high-frequency stages employ screen-grid valves with tuned anode-circuits, and the second stage is provided with Reinartz reaction. The two high-frequency stages are screened from one another and from the detector valve. The whole range of frequencies is covered by sets of plug-in coils. These coils are wound on ribbed ebonite formers, the windings being spaced, and are tuned by condensers having a maximum capacitance of $0.00024 \mu\text{F}$. The method of construction of one of the coils is shown in Fig. 6. The anodes and screen-grids of the high-frequency valves are decoupled in a normal manner by means of condensers and resistances.

Leaky-grid detection is used in this receiver, the grid condenser having a value of $0.0001 \mu\text{F}$ and the resistance of the grid leak being 1 megohm. One of the problems in the design of a receiver of this type is to avoid threshold howl when the reaction is increased just beyond the oscillating point. This difficulty was examined theoretically and practically by L. S. Alder,* and as a result it has been overcome by connecting the grid leak of the detector valve to a point near the negative end of a potentiometer across the filament battery, at the same time shunting the choke in the anode circuit of the detector valve by a resistance of 20 000 ohms, thus preventing the anode circuit from having an inductive reactance at fairly high frequencies.

The actual coupling between low-frequency stages is by means of choke capacity. The chokes have an inductance of 10 henrys, are wound on closed iron cores, and are shielded by iron and copper cases. This double shrouding has been found to be necessary in order to avoid coupling between the choke and other components

* *Experimental Wireless*, 1930, vol. 7, p. 197.

in the receiver, and direct pick-up by the choke of low-frequency electrical interference from motors, fans, etc. The chokes also perform the functions of telephone transformers, each choke having a secondary winding of $6\frac{1}{2}:1$ ratio. The output terminals of the receiver can be connected to any one of these secondary windings by means of a 3-way switch. No external telephone transformer is therefore required, whilst the telephones can be connected after either the detector valve or the first or second stage of note magnification. This

operation but may be opened in order to allow a separate anode supply to the last valve when more power is required from the output than can be obtained from the normal general-purpose valve. Grid-bias terminals are also provided for the output valve, so that a power valve can be employed in this position if desired. These terminals are also closed by a link for normal operation with general-purpose valves.

Two filament rheostats are provided; the first controls the filament current of the two high-frequency screen-

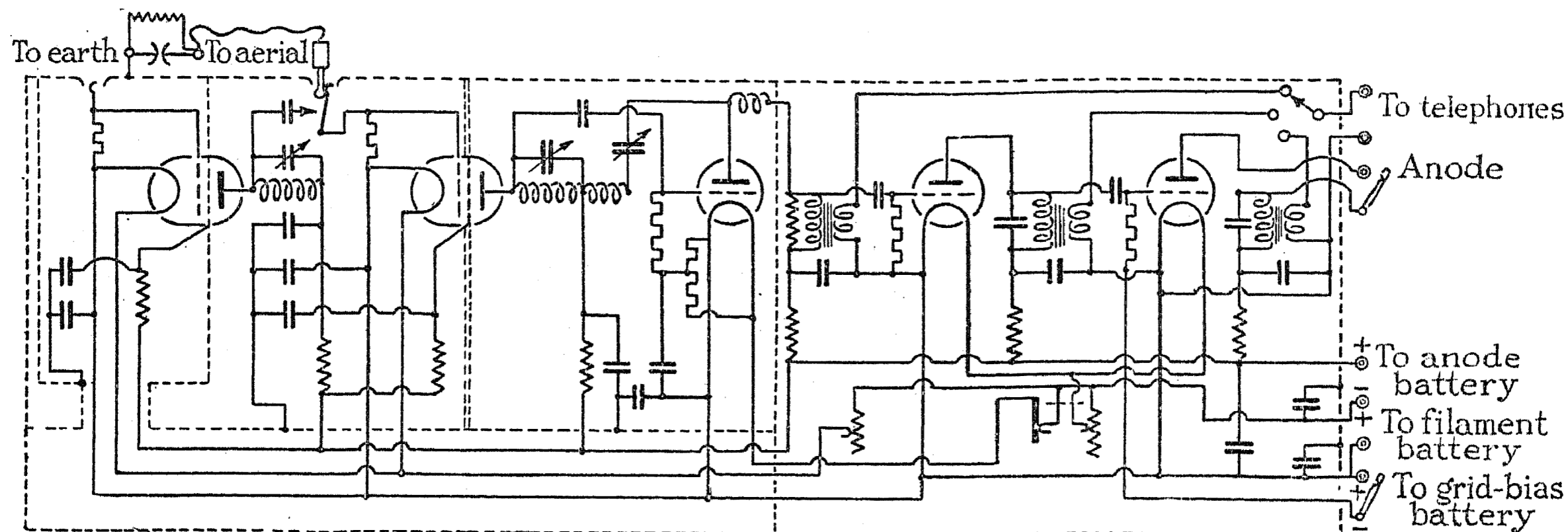


FIG. 5.—High-frequency receiver.

arrangement is adopted in order to avoid a defect which arises when telephones and telephone transformers are moved from the anode of the detector valve to the anode of a stage of note magnification, for in the case of an oscillating detector this almost invariably upsets the

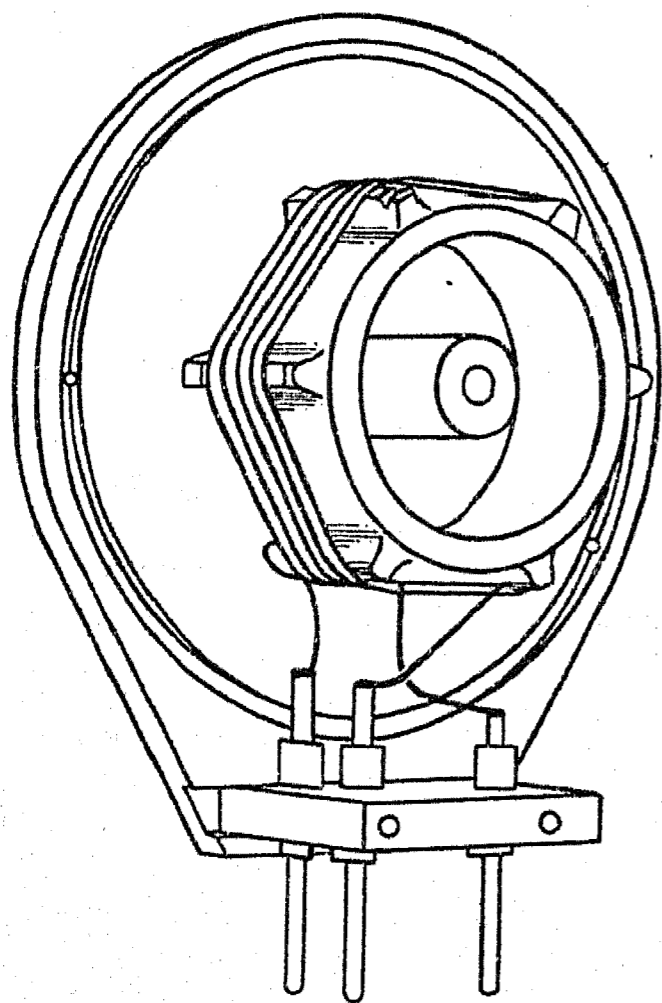


FIG. 6.—Plug-in coil.

reaction adjustment. This method of using the choke for the dual purpose of choke and telephone transformer makes it possible to switch without any appreciable alteration of the reaction setting. It will be noticed that the anode of the last valve is brought out to a terminal and thence through a link to a terminal connected to the final choke. This link is closed for normal

grid valves; the second controls the note-magnifier stages and, in addition, carries a make-and-break switch which breaks the detector filament circuit in the "off" position. These two rheostats are used to regulate the amount of high- and low-frequency amplification, and since in all positions of these rheostats the detector valve has full filament voltage this can be done without any large change in tuning.

The condenser dials of this receiver are interesting since they must allow the following requirements to be fulfilled: (a) Quick search over the whole scale. (b) Slow-

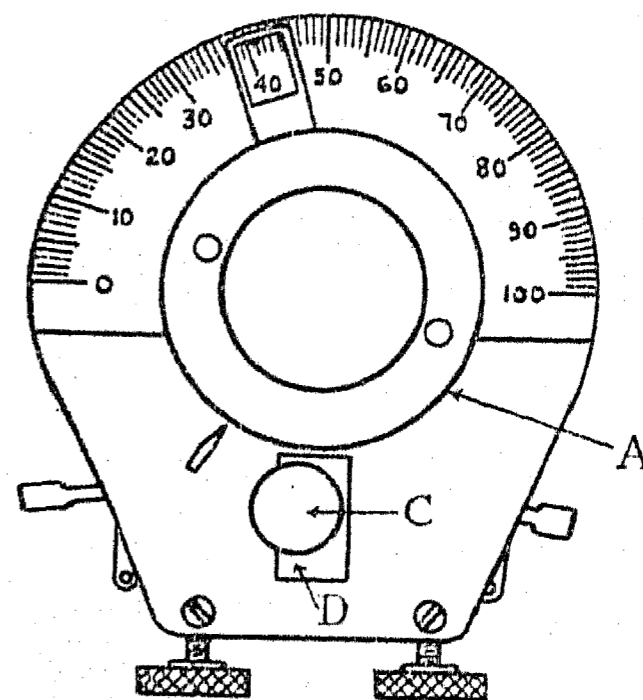


FIG. 7(a).—Receiver condenser dial.

motion control. (c) Instantaneous setting to either of two predetermined readings. (d) Slow-motion control at either of these settings, without disturbing the other one. A dial designed to meet these conditions is illustrated in Fig. 7(a). It operates in the following way. The main handle A is rigidly connected to the condenser spindle, and quick-search or wave-changing operations are carried

out with this handle. A crown wheel is secured to the condenser spindle. A knob C is attached to a secondary spindle carrying a scroll at its lower end. A spring depresses this spindle, causing the scroll to engage the crown wheel. Rotation of the knob C will now cause rotation of the crown wheel and condenser spindle at a

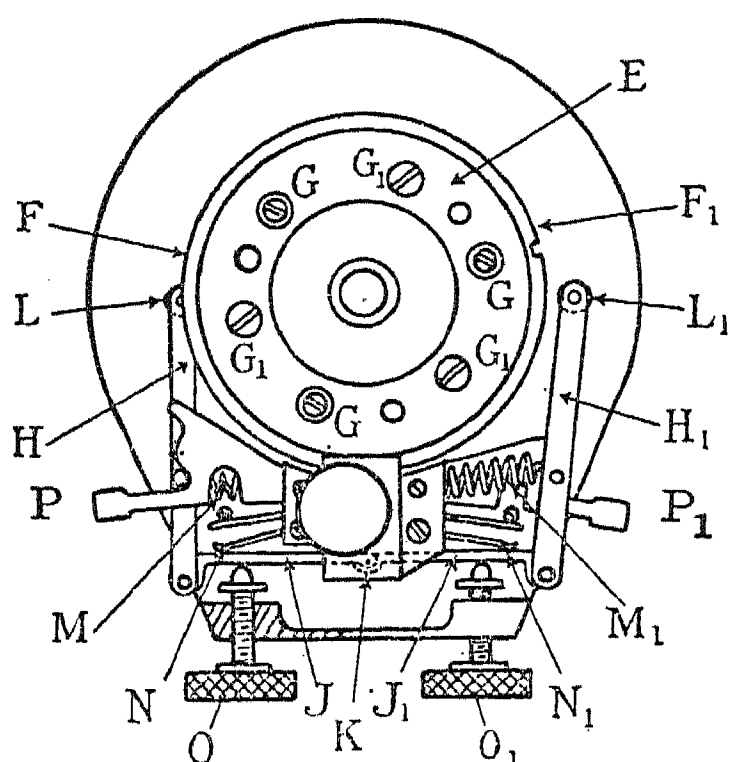


FIG. 7(b).—Receiver condenser dial (covers, etc., removed).

reduced rate determined by the gear ratio of scroll to crown wheel. When the knob C is pulled up, the scroll is disengaged from the crown wheel and the detent plate D is pushed outwards by a spring which engages a shoulder on the secondary spindle, thus holding the gears out of mesh and leaving the condenser free. In Fig. 7(b) the dial is shown with covers, main handle, and scale removed. A central fitting E, keyed to the

to snap into the notches in the rings as they pass, thus giving a definite location at the angular positions predetermined by the setting of the rings before clamping. The links J, J₁, on which the roller frames are pivoted turn about a common centre K. Springs N, N₁, keep these links pressed against the points of the screws O, O₁. Turning these screws thus causes the links to turn about the centre K, moving the roller frames and turning the condenser spindle. The relative sizes of the rollers and notches ensure a definite holding, but this holding is not so firm that it cannot be overridden by means of the slow-motion handle. Two cam plates P, P₁, are provided. On depressing these the roller frames are pushed and held outwards, lifting the rollers from the edges of the rings and so putting the quick wave-changing device out of action. In operation the dial may thus be used as follows:—

(i) *Quick search*.—Depress the cam plates P, P₁, pull out the knob C, and the dial is now quite free. For slow motion or fine tuning depress the cam plates P, P₁, and push in the detent plate D. The scroll and crown wheel are now engaged and the dial can only be actuated by the knob C, giving a gear ratio of 100 : 1. In addition, the condenser is locked in the position in which it is left, since the scroll and crown-wheel gear is irreversible.

(ii) *Quick wave-change to predetermined readings*.—Lift the cam plates P, P₁, and pull out the knob C. On rotation of the handle, two positions will be found at which the rollers snap into the notches in the steel rings. These correspond to the two nominal frequencies required, but a fine adjustment can be made if necessary

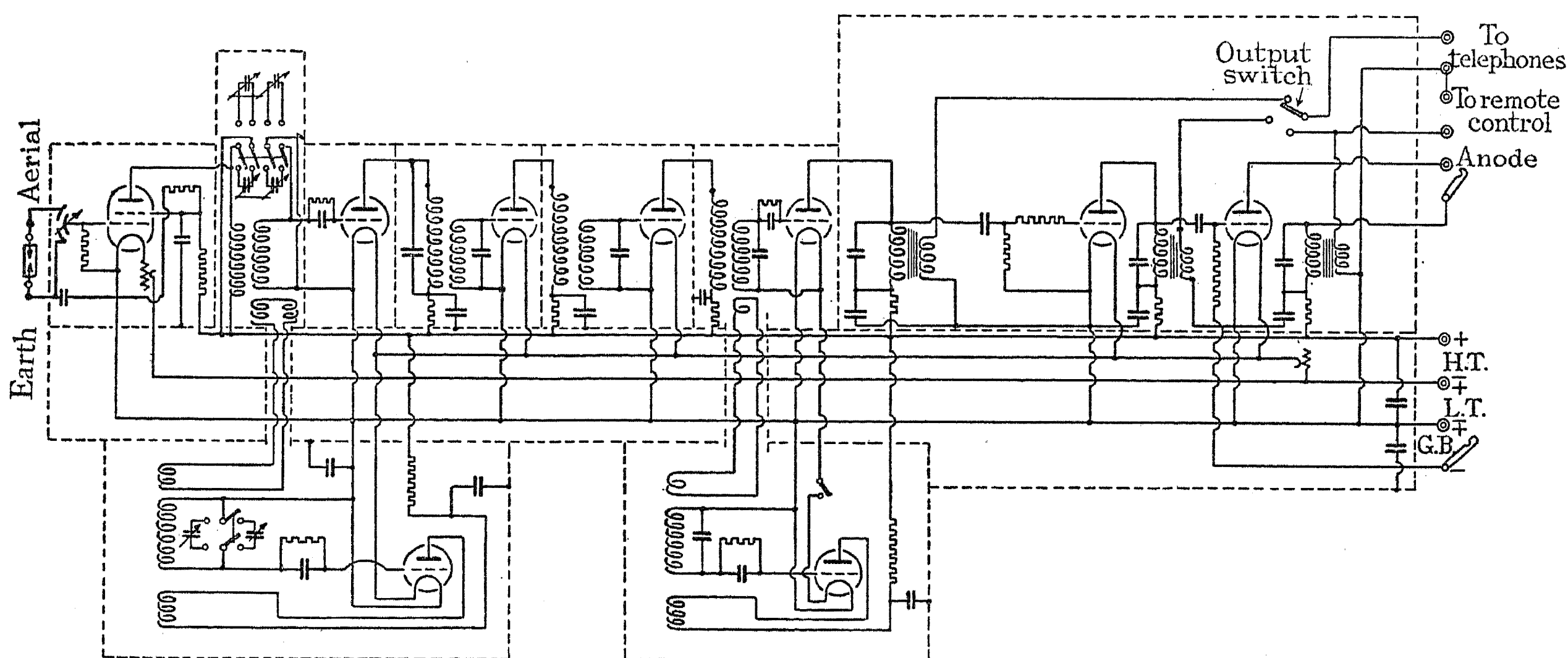


FIG. 8.—Medium-frequency receiver.

condenser spindle, carries two steel rings F, F₁, one above the other. These rings are rotatable and may be clamped independently of one another at any angular position by the screws G, G₁. A notch is cut in each ring. Two steel frames H, H₁, are pivoted on links J, J₁. Each of these frames carries a roller L, L₁, respectively. Springs M, M₁, pull the roller frames inwards and cause the rollers to run on the edges of the steel rings F, F₁, and

with the screws O or O₁. The two click positions can be adjusted to any predetermined readings by slacking the locking screws G and rotating the steel rings F and F₁.

Medium-Frequency Receiver.

This covers the frequency range 150–1 500 kilocycles per sec. Both high selectivity and high amplification, together with quick wave-changing, are required. The

superheterodyne principle is therefore used, and the circuit diagram is as shown in Fig. 8.

The aerial circuit of the receiver is untuned, and the aerial is connected to one set of fixed plates of a differential condenser, the grid of the isolating valve to the movable plates, and the earth to the other set of fixed plates. A 100 000-ohm grid leak also joins the grid of the valve to its filament. The whole system is protected by a gas-gap type lightning arrestor connected between aerial and earth. The primary of the tuner is connected to the anode circuit of the screen-grid valve and is magnetically coupled to the secondary, which forms the tuned grid-circuit of the first detector valve. The coupling is fixed. The primary and secondary tuning condensers are gang-controlled. This is possible since the aerial is isolated from the tuner by the first screen-grid valve, so that neither tuned circuit is dependent to any appreciable extent on the type or size of aerial used. The first heterodyne, which is of the tuned grid type, is coupled to the tuner secondary through a link circuit consisting of two coupling coils and a small loading inductance, to prevent over-coupling on the highest

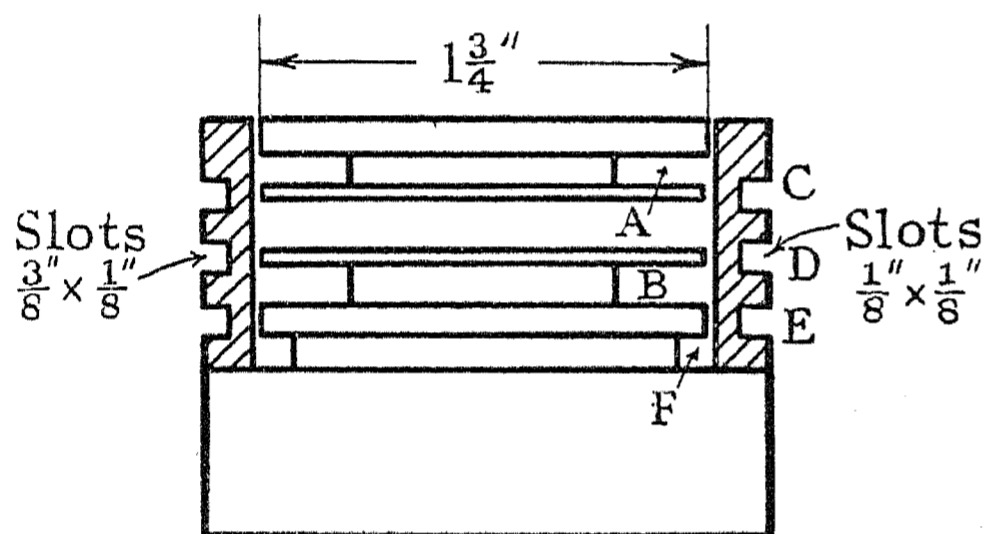


FIG. 9.—Former for intermediate-frequency transformer.

frequencies. Both the tuner and the first heterodyne cover the range 150–1 500 kilocycles per sec. in four steps, and the inductance range switches for both are gang-controlled. Tuner and heterodyne windings are close-wound on formers of ebonite tubing.

Both detectors are of the leaky-grid type and the anode supply to each is decoupled by means of wire-wound resistance rods. The two intermediate-frequency stages employ general-purpose valves, and the coupling is by means of tuned grid transformers. The three intermediate-frequency transformers are identical, and details of the formers are shown in Fig. 9. To avoid the use of semi-variable condensers for tuning these stages, the grid coil is wound in two halves on separate formers A and B, and consists of 500 turns of No. 38 S.W.G. enamelled and double-silk-covered copper wire wound in each of the slots A and B and joined in series. The coupling between the two formers A and B is variable by means of a screw adjustment, giving a total grid-inductance variation of 25 to 30 per cent. With this arrangement fixed mica condensers of nominal value $0.0011 \mu\text{F}$ can be used. The anode winding is wound on a former concentric with the grid formers, and consists of 220 turns of No. 44 enamelled and double-silk-covered copper wire wound in each of the slots C, D, and E, joined in series. The transformer preceding the second heterodyne carries the coupling coil to the second heterodyne, which consists of one turn of No. 38 enamelled

and double-silk-covered copper wire. A by-pass condenser of $0.00044 \mu\text{F}$ is connected across the anode coil of the transformer following the first detector.

The second heterodyne is also of the tuned grid type, the only variation in tuning being obtained by a variation of the grid inductance in the manner used for the intermediate-frequency transformers. In order to reduce the interference as much as possible between the two heterodynes a high ratio of capacitance to inductance is used in this grid circuit, the tuning condenser having a value of $0.0044 \mu\text{F}$. The grid winding consists of 220 turns of No. 38 enamelled and double-silk-covered copper wire wound in slot D (Fig. 10), joined in series with 250 turns of No. 38 enamelled and double-silk-covered copper wire wound in slot B. The variation in coupling obtainable between the two portions of the grid winding provides sufficient variation in heterodyne tuning, and the correct tuning, having once been found, needs no further adjustment. The anode coil consists of 150 turns of No. 38 enamelled and double-silk-covered copper wire wound in the slot A. The coupling coil consists of 1 turn of No. 38 enamelled and double-silk-covered copper wire wound in slot C.

The coupling between the low-frequency stages is by

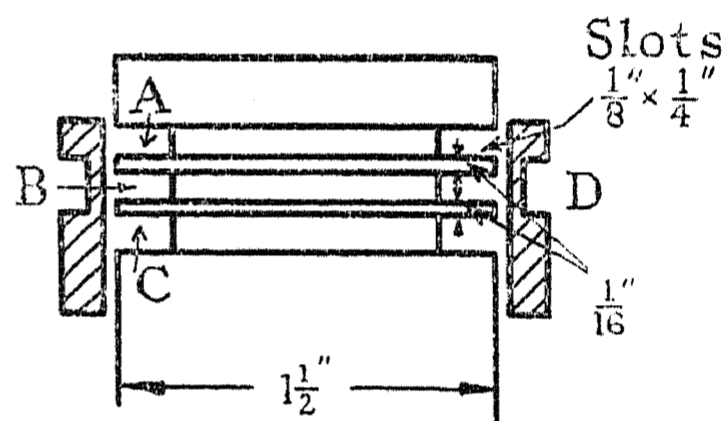


FIG. 10.—Former for second heterodyne coils.

means of choke capacitance. It is identical with that previously described for the short-wave receiver, and similar arrangements are made as regards the output valve.

From the receiver diagram it will be noted that two tuning dials and two heterodyne dials are fitted. Only one tuning dial and one heterodyne dial are used in tuning in one signal, but it is possible by means of a change-over switch to use either of the two alternative sets of tuning and heterodyne dials. Since the dials are of the quick-wave-change pattern previously described, it is possible to pre-set four frequencies on this model and to change from any one to any other of these pre-set frequencies either by means of the clicks on the dials or by means of the change-over switch.

Long-Wave Receiver.

The frequency range to be covered by this receiver is 15–550 kilocycles per sec., and difficulties arise owing to a clash between the requirements of wave range and selectivity on the one hand and mechanical size on the other. Components, such as condensers and inductors, must have large values, and it proved to be impossible to build this receiver into a single screened box. It was therefore divided into three separate units—a tuner, a radio-frequency amplifier, and a note-magnifier and note-selector unit.

The tuner unit will be considered first, and a diagram of connections is given in Fig. 11. As will be seen from

this, the tuner is of the 2-circuit type and the primary and secondary circuits are enclosed in separate screened compartments formed in the aluminium box. Both primary and secondary coils are space-wound in four sections using 3/32 S.W.G. enamelled and silk-covered

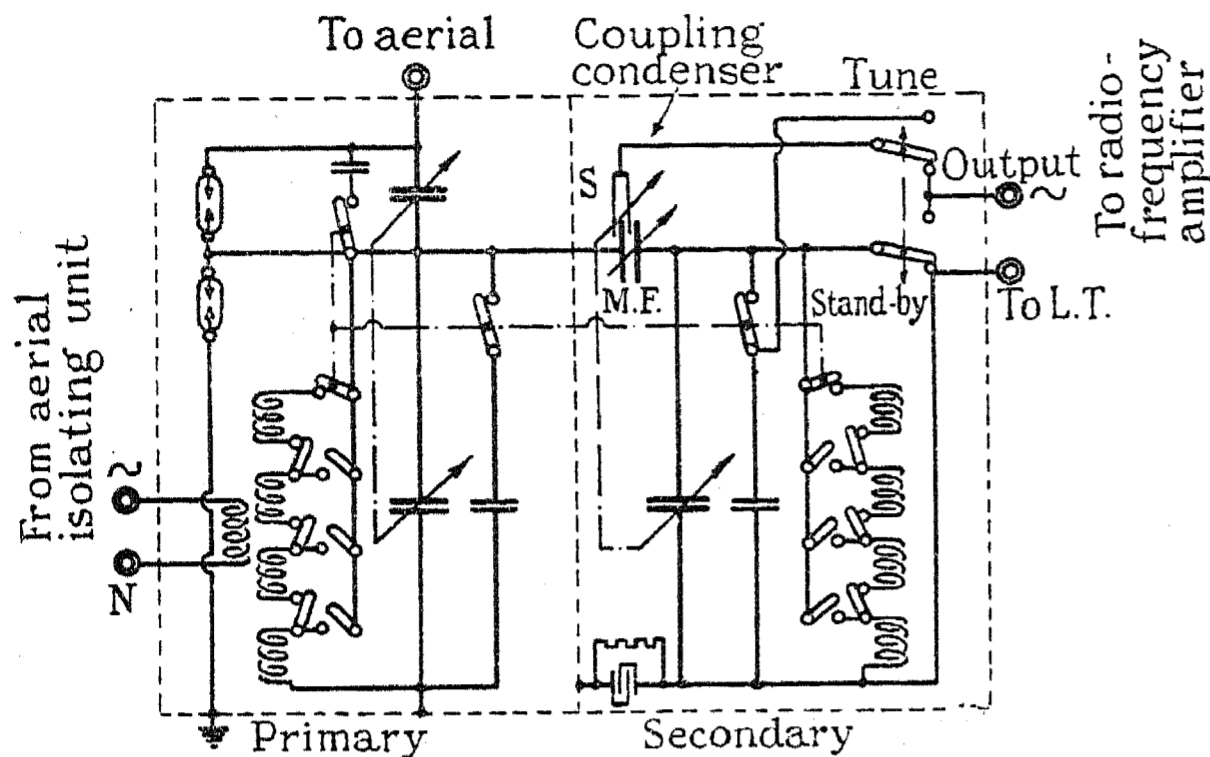


FIG. 11.—Internal connections of low-frequency tuner.

stranded wire. The sections are joined in series to give the inductance required for the lowest frequency-range, and the larger sections are disconnected for the high frequency-ranges, the largest of all being short-circuited when the two highest frequency-ranges are in use. Fig. 12 shows diagrammatically the various sections of the coils and gives details of the windings.

The size of the screened boxes is fixed within narrow

when contained in the screens the decrement is at worst of the order of 0.037.

Returning now to Fig. 11, it will be seen that the left-hand compartment contains, in addition to the primary circuit, the coupling coil for the aerial isolating valve (wound in four sections outside the primary inductance), and the aerial series condenser ganged to the tuning condenser. The secondary compartment contains a special coupling condenser, described below, and a stand-by/tune switch. The tuned circuits are identical in every respect. Connections to the four sections of each inductance are controlled simultaneously by a ganged range-switch which has five positions. When the handle of this switch is in position 5 the smallest sections of the inductances are connected while the two largest sections are short-circuited to prevent them tuning on their own self-capacitance. With the switch in position 4, the second section of the inductance is connected in series with the first, whilst the largest section still remains short-circuited. When the switch is moved to position 3, one of the larger sections is added, whilst in position 2 both the larger sections are added. In position 1, additional fixed condensers are placed in parallel with the tuning condensers and the aerial coupling condenser. The reasons for this addition of fixed condensers instead of further sections of inductance are to avoid the mechanical size of the inductances required to tune down to frequencies of the order of 15 kilocycles per sec., and to prevent the ratio L/C for the circuit becoming too large. The tuning condensers have a maximum capaci-

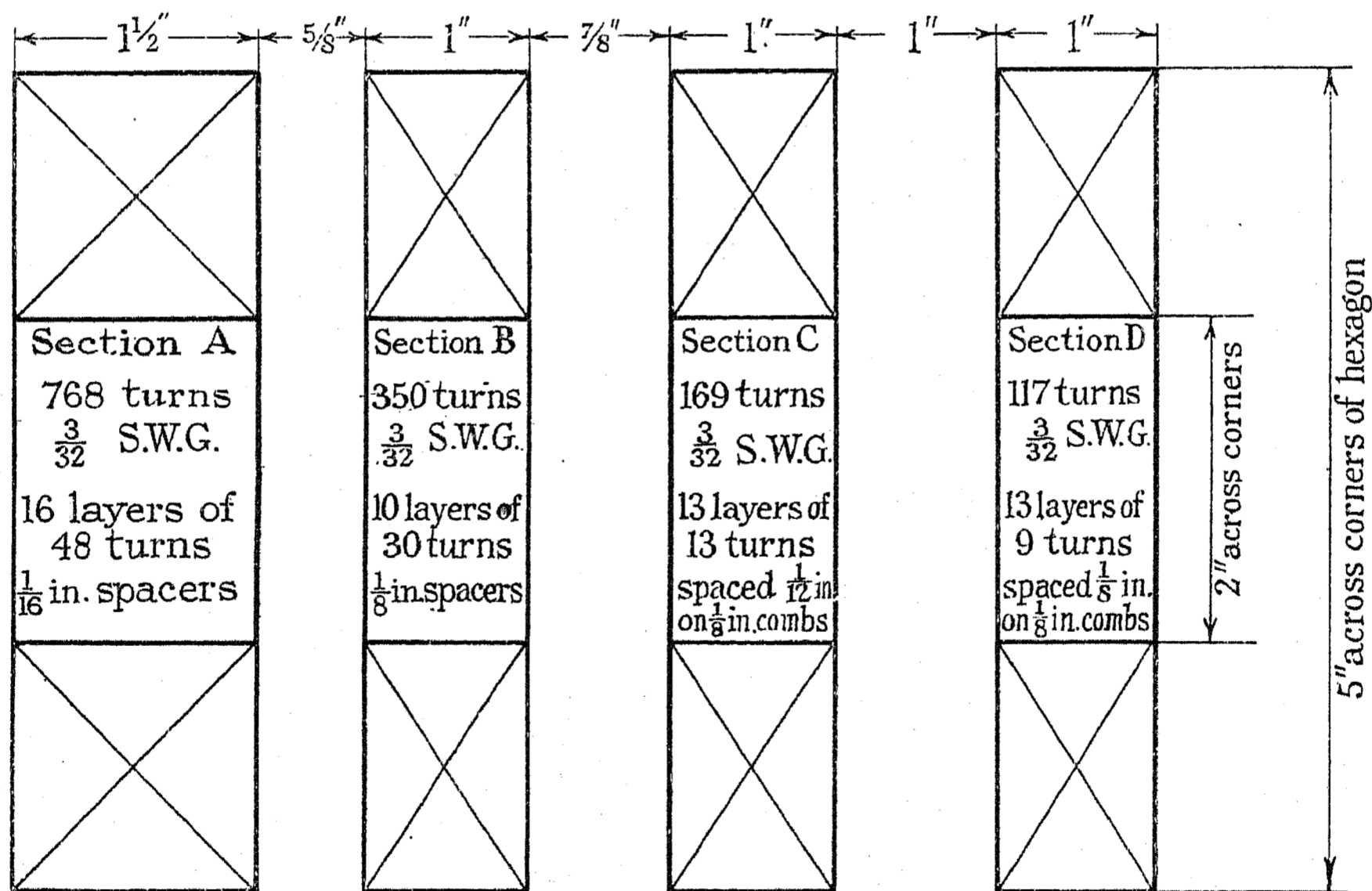


FIG. 12.—Coils for low-frequency tuner.

limits by mechanical considerations of the overall size of the receiver, and theory gives little help in the determination of the best form of tapped inductance to be fitted into a given space. The winding data had therefore to be obtained from experimental tests on coils of different shape and size, these tests taking the form of decrement measurements. The efficiency of the various coils finally developed may be judged by the fact that

tance of 0.00132 μ F. They are of the square-law type, made up from standard naval die-cast condensers, the fixed plates being shaped to give the square law. The aerial coupling condenser has a maximum value of 0.00033 μ F. The additional fixed condensers in position 1 of the range switch are 0.0011 μ F for the tuned circuits and 0.00022 μ F for the aerial coupling condenser. The numbering of the stops mentioned above perhaps

needs some slight explanation. In naval practice the minimum settings of the variable condensers correspond to the maximum dial readings. This enables the dials to carry rough calibrations in kilocycles per sec., and increase in condenser scale reading corresponds to increase in frequency. The same applies to range-switch numbering. Before describing the tuner circuit more fully it is proposed to state the actual use of the stand-by/tune switch. This switch is so arranged that when it is in the "stand-by" position only the tuned aerial circuit is in use, the secondary circuit being disconnected from the receiver. When it is in the "tune" position the two circuits are in use and are capacitance-coupled. In the tune position the small coupling condenser is varied automatically with the tuning of the secondary circuit, and, in addition, it can be varied independently by means of an external handle. This small condenser has been specially designed for this particular use. Its construction can be seen diagrammatically from Fig. 11.

prove too small. To overcome this difficulty its capacitance is increased by adding to it the capacitance between the moving plate and the screen of the coupling condenser, the capacitance being of the order of $20 \mu\mu\text{F}$.

This is accomplished, as can be seen from the diagram of connections, by connecting the coupling-condenser screen permanently to one side of the $0.0011\text{-}\mu\text{F}$ condenser, which is added to tune range 1. In all other positions of the range switch this $0.0011\text{-}\mu\text{F}$ condenser is disconnected from the tuned circuit and thus provides an effective earthing path for the screen of the coupling condenser. When the stand-by/tune switch is rotated into the stand-by position, the secondary circuit is short-circuited, whilst the primary circuit is connected to the grid of the first valve of the amplifier through the capacitance between the moving plate and the screen of the coupling condenser.

A circuit diagram of the radio-frequency amplifier

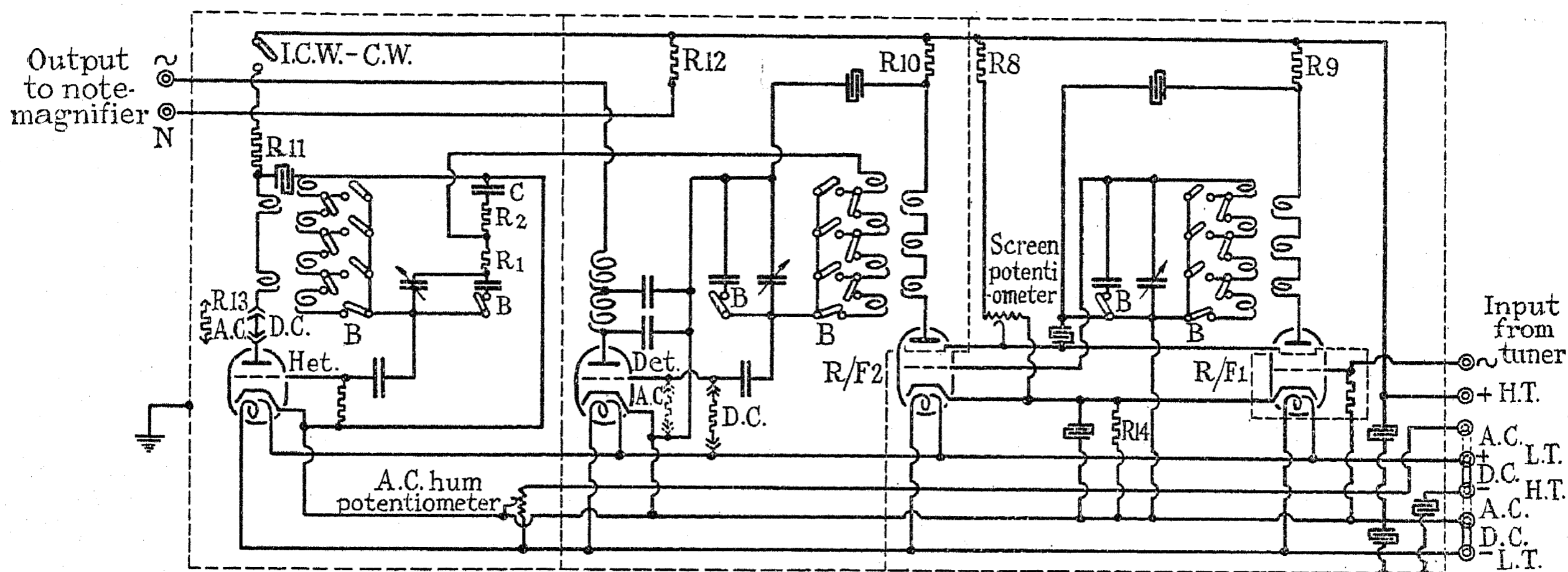


FIG. 13.—Internal connections of radio-frequency amplifier.

The fixed and moving plates F and M are half-cylinders, and the inner or moving plate can be rotated by the external dial to vary the coupling capacitance. Between these two plates a cylindrical screen S is made to slide in an axial direction by a lever which is actuated by a cam on the end of the secondary tuning-condenser spindle. This cam is so shaped that the effective capacitance between fixed and moving plates of the coupling condenser varies with the tuning of the secondary circuit to give practically constant selectivity over the whole range of the receiver, but, in addition, the selectivity can be varied at will by rotating the moving plate of the condenser by means of the external handle. It should be pointed out that the maximum effective capacitance of this condenser between fixed and moving plates is $3 \mu\mu\text{F}$. The minimum value of the capacitance, which occurs when the secondary tuning condenser is also at minimum, is very small, too small, in fact, to be measured by ordinary laboratory apparatus. In position 1 of the range switch, i.e. for the lowest frequencies, the tuning condensers are increased by the $0.0011\text{-}\mu\text{F}$ fixed condensers thrown in parallel. Hence on this range the coupling condenser would of necessity

connections is given in Fig. 13. The amplifier box itself is divided into three separate screened compartments. The right-hand compartment contains the first screen-grid valve, the first tuned interval circuit, and the valve holder and base of the second screen-grid valve. The upper portion of this valve projects through a hole in the screen into the centre compartment of the amplifier, which contains the second tuned interval circuit, the detector valve, and the output circuit from the detector to the note magnifier. The left-hand compartment contains the heterodyne valve and its tuned circuits. Each valve is decoupled in the normal manner by means of resistances and condensers, the various resistances and condensers being placed in the compartments to which they belong. The radio-frequency stages are coupled by tuned grid transformers. The grid inductances are wound in four sections of similar value to those used in the tuner, and the connections are made by ganged range switches similar to those used in the tuner. Since these coils are of necessity shunted by the anode and grid circuits of the valve, efficiency is not of such great importance as in the case of the tuner coils, and they are therefore wound in slots in ribbed

ebonite formers, each section being subdivided into several slots. The anode coils, which are nominally aperiodic, are wound on cylindrical paxolin formers outside the grid coils. The anode coils are each wound in three sections, permanently connected in series but so spaced relatively to the grid inductances as to give approximately equal amplification on all five ranges. The tuning condensers are of the square-law type and are similar to those fitted in the tuner. The amplification of the radio-frequency valves can be controlled by means of a 10 000-ohm potentiometer which varies the screen-grid potential. The heterodyne uses a tuned grid circuit of which the grid inductance is identical with those in the amplifier. The anode coil, which in this case is a reaction coil, is similarly wound on a cylindrical former surrounding the grid coil, but in this case there are only two sections of winding, so spaced

in the amplifier but is provided with a slow-motion dial for fine adjustment and for locking it in position. Since the receiver must cover such a wide range of frequencies, it is essential that the heterodyne should be switched off when using the amplifier for reception in the I.C.W. and spark-wavelength bands, i.e. at the higher-frequency end of its scale. A switch is therefore fitted marked "C.W./I.C.W.," which makes or breaks the high-tension supply to the heterodyne. The detector valve is the naval general-purpose valve, and works on the leaky-grid principle. The connection between the amplifier and the note magnifier is via a 2-stage low-pass filter, with a cut-off arranged at about 7 000 cycles per sec. This was found to be necessary owing to the fact that the amplifier must work on frequencies down to 15 kilocycles per sec., and a single radio-frequency choke proved insufficient to prevent high-frequency potential of this

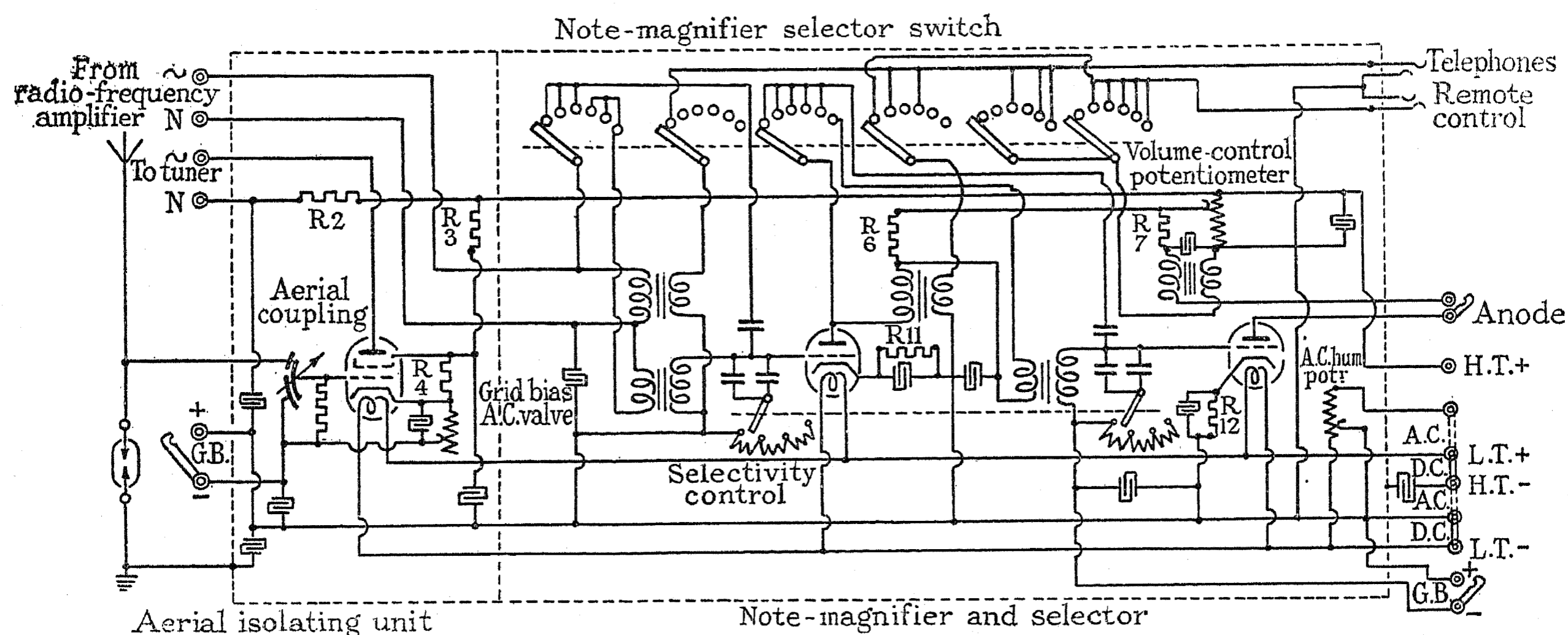


FIG. 14.—Internal connections of note magnifier.

as to give approximately constant heterodyne strength on all ranges.

The coupling of the heterodyne to the detector circuit was the subject of considerable experimental work. The method finally adopted can be seen from Fig. 13. Two resistances R_1 and R_2 (100 ohms and 4 ohms respectively) and a $0.5\text{-}\mu\text{F}$ condenser C , are connected in series with the oscillating circuit of the heterodyne. The 4-ohm resistance R_2 and the condenser C are also connected in series with the tuned circuit of the detector valve. This arrangement gives a weak heterodyne coupling on the high frequencies where the tuning of the heterodyne circuit and the detector circuit differ slightly for a beat note of the order of 1 300 cycles per sec.; but on the lower frequencies, where the difference between the tuning of the heterodyne and detector circuits is large, the necessary increase in heterodyne coupling is obtained owing to the increase in impedance of the condenser C . By this method of coupling it has been found possible to avoid any serious interaction between the tuning of the two coupled circuits, i.e. the detector circuit and the heterodyne circuit. The tuning condenser of the heterodyne circuit is similar to the remaining tuning condensers

order from being passed to the note magnifier unless this choke was made of such a size as to introduce considerable attenuation, even on audio frequencies of less than 2 000 cycles per sec.

The circuit diagram of the note magnifier is shown in Fig. 14. The model is divided into two compartments. The left-hand portion contains an aerial isolating unit similar to that described for the high-frequency and medium-frequency receivers. This aerial isolating unit really forms part of the tuner circuit, and it was placed in its present position in the note magnifier merely from considerations of space and ease of arrangement. The right-hand portion of the amplifier contains two audio-frequency amplifying stages which can be connected either as note magnifiers or as note selectors. The method by which this is accomplished can be seen from the circuit diagram in Fig. 14. The anode lead from the detector valve in the radio-frequency amplifier is connected through a 10-henry choke in the note magnifier to the high-tension supply in the radio-frequency amplifier. A similar choke is connected in the anode supply of the first audio-frequency valve. The grids of the two audio-frequency valves are connected to

their respective filaments through inductances which are sharply tuned to 1 350 cycles per sec. by means of parallel condensers. These inductances are fitted with primary windings having a small number of turns and giving a step-up ratio of 1:150. To connect a stage as a note magnifier, the anode of one valve is joined through a $0.01\text{-}\mu\text{F}$ condenser to the grid of the next valve, the 10-henry inductance mentioned above acting as anode choke for the first valve. Under these conditions the anode-filament impedance of the previous valve is connected in parallel with the tuned grid circuit, and this anode-filament impedance is very much smaller than the parallel impedance of the tuned grid circuit when at its resonant point, i.e. very much smaller than the ratio L/CR for the tuned grid circuit. As a result of this the resonance peak of the tuned circuit is very small and the stage is virtually non-selective. When it is desired to connect a stage as a note selector, the anode of the valve is connected to the primary winding of the tuned inductance. In this case the damping on the tuned circuit due to the impedance of the previous valve is reduced to a negligible value owing to the large step-up ratio of the tuned transformer, and the full selectivity of the circuit is obtained. The inductances are built up on stalloy cores having a small air-gap. These inductances have a value of about 10 henrys and a decrement of the order of 0.05. Each inductance is tuned to 1 350 cycles per sec. by means of a $0.00055\text{-}\mu\text{F}$ adjustable condenser in parallel with a $0.0011\text{-}\mu\text{F}$ fixed condenser. It has been found necessary to enclose each inductance, and the various fixed condensers belonging to the stage, in a separate sheet-iron cover to reduce the effects of electrostatic and magnetic coupling between the stages and the effects of pick-up from stray electromagnetic fields. This tendency to stray coupling has been found to be one of the major disadvantages in the use of unclosed iron cores, but it had to be accepted in order to obtain coils with a sufficiently low decrement. The selectivity of the tuned stages is of such a value that a slight amount of ringing or belling is liable to occur when receiving morse signals at hand speed. Provision has therefore been made to increase the decrement of the circuits up to a value of 0.3 by means of resistances which can be inserted into the circuits by a 4-way switch marked "Selectivity Control." The 10-henry anode chokes, in addition to the primary windings, carry a secondary winding so that they may be used as telephone transformers in a manner similar to that already described for other receivers. The switching for this note-magnifier note-selector has proved to be somewhat complicated. In naval practice it is essential to be able to read a signal in two positions in the ship, one close to the receiver, the other usually some considerable distance away. The receiver is therefore arranged so that the distant position is fed by one more stage of note magnification than that used by the operator in the office. Where note selection is used, however, it is essential to guarantee that the operator in the office cannot switch one or more of the note-selecting stages between himself and the distant position; hence the switching for the note-magnifier note-selector requires six separate positions to avoid any risk of this occurring.

As will be seen from the circuit diagrams, this receiver outfit has been so designed that it can work either from battery supplies (using ordinary battery valves) or from an a.c. supply, in which case indirectly heated valves can be fitted.

In order to accomplish this, the supply terminals to each model are provided with a pair of links which may be connected in positions marked "A.C." or "D.C." In the a.c. position a common busbar, to which all decoupling condensers, earthing condensers, and the cathode leads to the indirectly heated valves, are joined, is connected to H.T. negative and to the sliders of potentiometers connected across the L.T. supply. These potentiometers are so adjusted as to reduce the hum due to the a.c. supply to a minimum. With the links in the d.c. position, the common earthing busbar is connected to L.T. negative and the hum potentiometers are disconnected. The H.T. negative terminal is joined to L.T. positive, to conform with naval practice. When changing from "A.C." to "D.C.," besides changing over the links it is necessary to change the grid leak of the detector valve from the cathode to the L.T. positive lead. Provision is made for this by fitting two pairs of grid-leak clips, marked "A.C." and "D.C."

This provision for working under two different conditions has to some extent complicated the wiring of the models, but this was unavoidable as they are occupying an interim position between the time when naval receivers are run from batteries and the time when they will be run on a.c. supplies; so that they must be capable of being fitted into ships in which either condition exists.

Stand-By Receiver.

The three receivers so far described form the main lines of reception in all ships, and the object of the stand-by receiver is to provide an alternative to any line in the event of a breakdown. It is therefore capable of receiving signals throughout the band of 15-20 000 kilocycles per sec. The essential conditions to be fulfilled by this receiver, in addition to its enormous frequency range, are: (a) Simplicity of design, so that it is unlikely to develop any defects in itself. (b) Ease and rapidity of tuning to any frequency that may be suddenly required.

To meet these requirements the stand-by receiver is therefore designed on the simplest possible lines, consisting of a detector with variable reaction followed by two stages of note magnification. Such a receiver contains none of the features which are desirable for reception of signals under Service conditions. Its selectivity and amplification are both very low, and, when it is used for C.W. reception with the detector valve oscillating, radiation must take place from the receiving aerial. This has been accepted, however, for this particular receiver in view of the fact that it will be used but rarely and then only in an emergency.

A circuit diagram of the receiver is shown in Fig. 15. The aerial is connected to the tuned grid circuit of the detector valve via a small coupling condenser. The value of this condenser is variable in steps by means of a 5-way switch, which connects one or more of four fixed condensers in series. In the first position of the switch,

the four fixed condensers are all in series and in addition are in series with the capacitance of the switch and leads. Thus in position 1 the coupling capacitance is very small indeed (only 1 or 2 $\mu\mu\text{F}$ due to stray capacitance), whilst in position 5 it reaches a maximum of 0.00033 μF . This wide range of aerial coupling is essential owing to the fact that on the highest frequencies the aerial and cable may at times be in tune as a multiple either of $\lambda/4$ or of $\lambda/2$, with consequent enormous changes in the damping thrown across the tuned circuit, whilst on the low frequencies a large coupling may be necessary to obtain adequate signal strength, or a very small coupling may be necessary to obtain some degree of selectivity.

The frequency range of the receiver has been divided into two parts, 15–1 500 kilocycles per sec. and 1 500–

The two separate tuning condensers are operated together by the same spindle, so that there is only one tuning-condenser dial on the front of the instrument. Both condensers are of the square-law type. Change-over from the high-frequency range to the low-frequency range is made by means of a 3-pole 2-way switch.

The actual frequency range covered by any coil (plug-in or fixed) depends upon the value used for the aerial coupling condenser, the size of the aerial, and the capacitance of the aerial trunk or cable. The ranges given above are therefore only approximate, and it is impossible to supply even a rough calibration with the receiver. It is left to the operators to produce their own tuning chart, corresponding to any particular aerial they may require to use.

Reaction, of the Reinartz type, is controlled at all

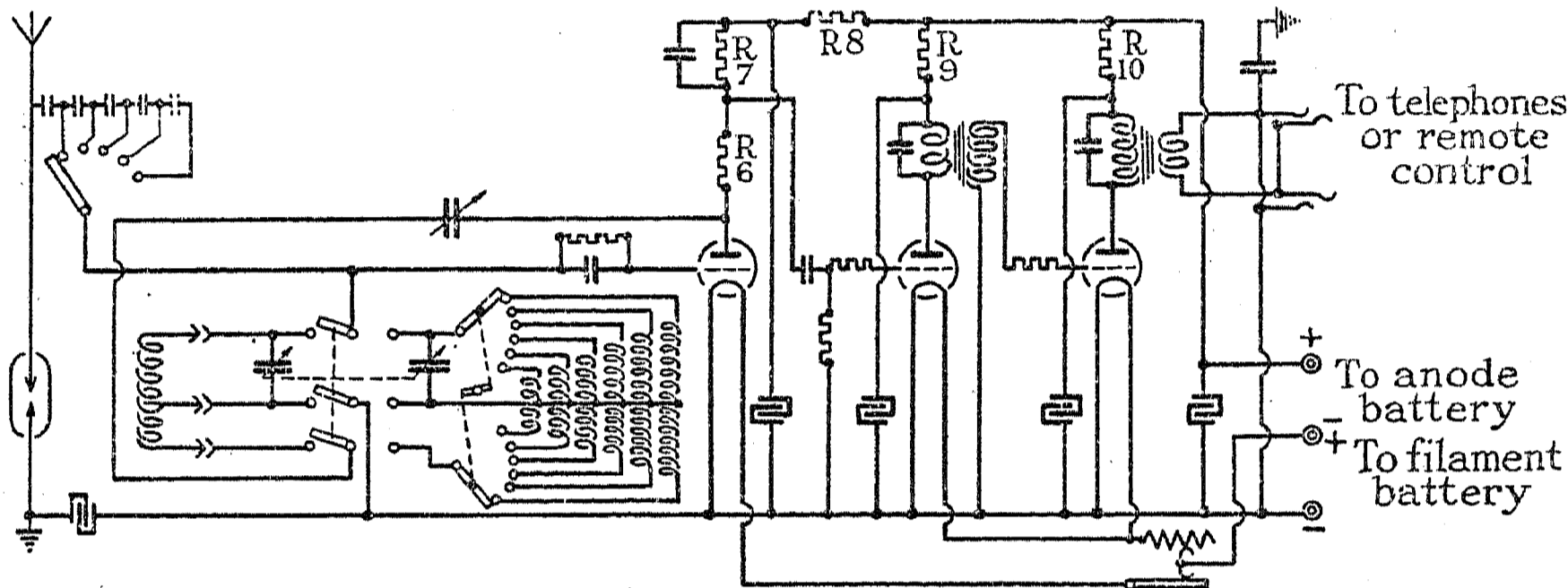


FIG. 15.—Stand-by receiver.

20 000 kilocycles per sec. The low-frequency range is covered by 6 fixed coils connected to a 6-way switch, together with a variable condenser having a maximum value of 0.0013 μF .

The frequencies nominally covered on the various positions of the range switch are as follows:—

Position of range switch	Frequency range (kilocycles per sec.)
1	15–32
2	32–70
3	70–150
4	150–320
5	320–700
6	700–1 500

The high-frequency range is covered by 4 plug-in coils and a variable condenser of maximum capacitance 0.00027 μF . The nominal frequency-ranges on the various coils are:—

Range coil	Frequency range (kilocycles per sec.)
1	1 500–3 000
2	3 000–6 000
3	6 000–11 000
4	11 000–20 000

frequencies by means of a square-law variable condenser of maximum capacitance 0.00038 μF .

Resistance-capacitance coupling is employed between the detector valve and the first audio-frequency amplifying valve. The anode resistance of the detector valve is 50 000 ohms and is shunted by a 0.0011- μF condenser as a radio-frequency by-pass. The coupling condenser is of 0.01 μF , and a resistance of 0.1 megohm is fitted in series with this condenser and the grid of the audio-frequency valve to act as a radio-frequency stopper.

In place of the radio-frequency choke usually fitted in the anode circuit of a detector valve with reaction, a resistance of 10 000 ohms is used, as it has not been found possible to design a choke to give smooth reaction over the whole of the frequency range required.

The coupling between the first and second audio-frequency valves is by means of a transformer with a $4\frac{1}{2}:1$ step-up. The primary of the transformer is shunted by a 0.0022- μF condenser, and a further 100 000-ohm resistance is fitted as a radio-frequency grid stopper.

A telephone transformer connects the anode of the last valve to a pair of low-resistance telephones.

Of the difficulties encountered in the design of this receiver, the two greatest were: (a) To obtain smooth reaction over the whole frequency range; and (b) to prevent radio frequencies from passing right through the receiver to the telephone leads, especially when working near the low-frequency end of the scale (i.e. around 15 kilocycles per sec.), since any radio frequencies in

these leads can couple back to the aerial and render the system unstable.

It is in order to deal with (b) that so many resistance stoppers and shunt condensers are fitted and that one of the telephone leads is connected to filament negative.

Non-Directional Receiver Using Crossed Frame Coils.

It is now proposed to describe a receiver which,

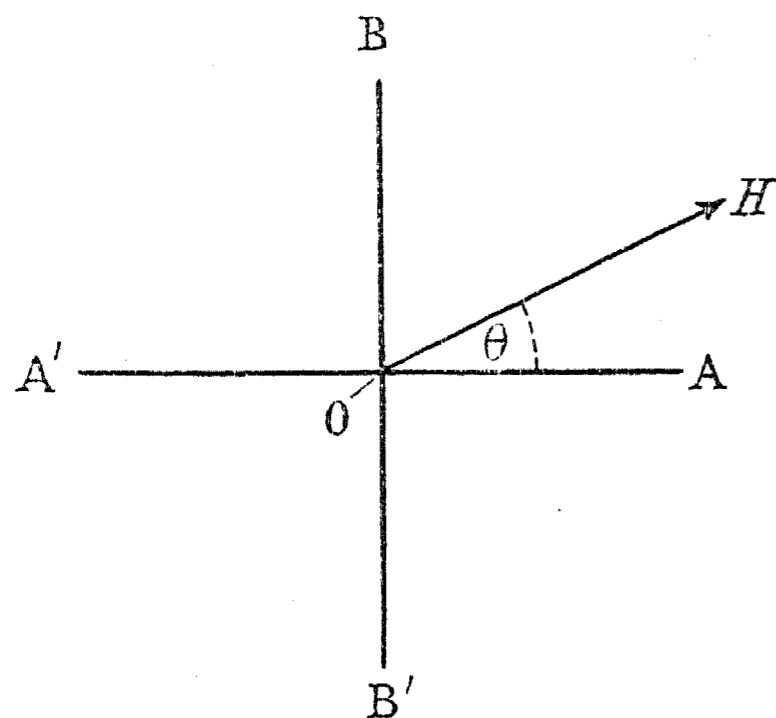


FIG. 16.

although not falling into the main line of development, has been produced to meet the requirement of non-directional reception in cases where space will only allow of the use of a frame coil or frame coils.

If two equal vertical frame coils are fixed at right angles and an incident plane wave with the magnetic

like a single frame coil in that they produce two maxima and two zeros.

When the case of two equal frame coils fixed at right angles is examined further, however, a way out of the difficulty can be found. In Fig. 16 the frame coils are represented in plan by the lines A'OA and B'OB. The plane of the wave-front is perpendicular to the paper and the magnetic field is represented by OH. The e.m.f. induced in the frame A'OA is $F \sin \theta \cos pt$ and that induced in B'OB is $F \cos \theta \cos pt$, where F is a constant dependent on the frame coils and the magnitude of the magnetic field, which is assumed to be $H \cos pt$. If by some means the currents or voltages produced in another circuit by these two e.m.f.'s can be made equal to $F' \sin \theta \cos \left(pt \pm \frac{\pi}{2} \right)$ and $F' \cos \theta \cos pt$ respectively, the resultant will be

$$F' \cos \theta \cos pt \mp F' \sin \theta \sin pt = F' \cos (pt \pm \theta) \quad (29)$$

The amplitude F' of this resultant is independent of θ . Rotation of the frame-coil system about the vertical axis, or, alternatively, rotation of the direction of the incident wave about the vertical axis, will result in a current of constant amplitude, but the phase will change continuously. By this means, therefore, two frame coils at right angles can be made to behave as a non-directional aerial system.

Fig. 17 shows in diagrammatic form a receiver which has been built up embodying this principle. The frame coils A, B, in Fig. 17 are coupled to the tuned grid

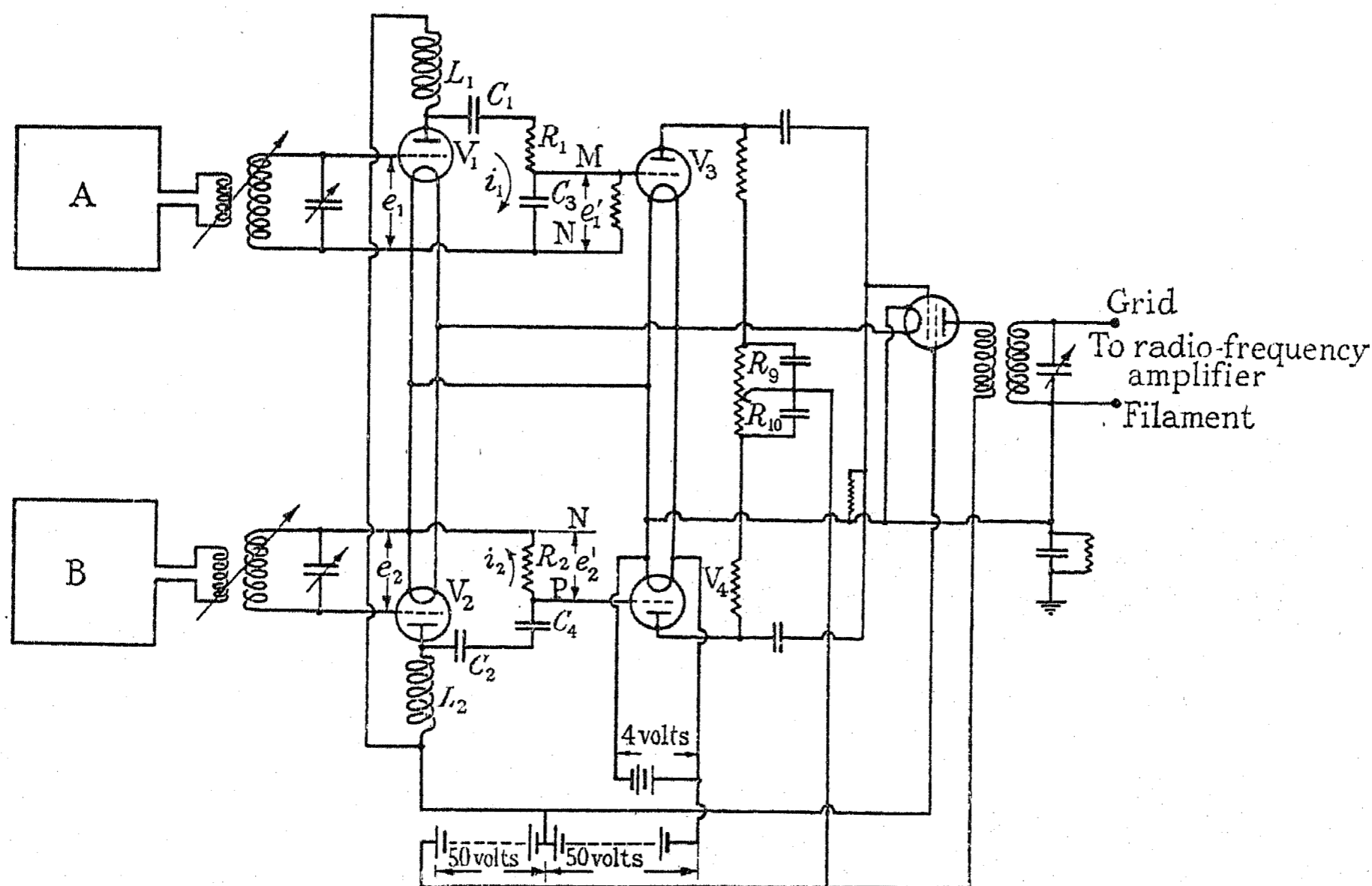


FIG. 17.—Phasing receiver.

vector horizontal is considered, the magnetic field of the wave must always cut at least one of these coils. It is well known, however, that if the two coils are connected either in series or parallel, and rotated as a whole about a vertical axis, there are two positions in which any given signal will produce no current in the external impedance joining the two free ends. Hence they behave

circuits of the valves V_1 and V_2 respectively. The d.c. anode voltage to these two valves is supplied via two equal radio-frequency chokes L_1 and L_2 . The high-frequency current from the valve V_1 takes the path: anode, C_1 , R_1 , C_3 , filament; whilst the high-frequency current from the valve V_2 takes the path: anode, C_2 , C_4 , R_2 , filament. Let the voltage e_1 applied between

grid and filament of the valve V_1 be represented by $F_1 \sin \theta e^{jpt}$, and the voltage e_2 applied between grid and filament of the valve V_2 be represented by $F_1 \cos \theta e^{jpt}$.

Then the currents i_1 and i_2 are given by

$$i_1 = \frac{\mu F_1 \sin \theta e^{jpt}}{(R_a + R_1) + \frac{1}{jpC_1} + \frac{1}{jpC_3}} \quad (30)$$

and

$$i_2 = \frac{\mu F_1 \cos \theta e^{jpt}}{(R_a + R_2) + \frac{1}{jpC_2} + \frac{1}{jpC_4}} \quad (31)$$

where R_a and μ are the anode impedance and amplifica-

If now $C_1 = C_2$ (these are large blocking condensers), $C_3 = C_4$, and $R_1 = R_2$, the currents i_1 and i_2 are in phase. On the other hand, the voltage e'_1 across the condenser C_3 is lagging by $\pi/2$ on the voltage e'_2 across the resistance R_2 . If now $R_2 = 1/(pC_3)$, then

$$\frac{|e'_1|}{|e_1|} = \frac{|e'_2|}{|e_2|} \quad (34)$$

in magnitude.

Thus the voltages applied between the grid and filament of the valves V_3 and V_4 respectively are proportional in magnitude to the e.m.f.'s induced in the frames A and B by the magnetic field, but differ in

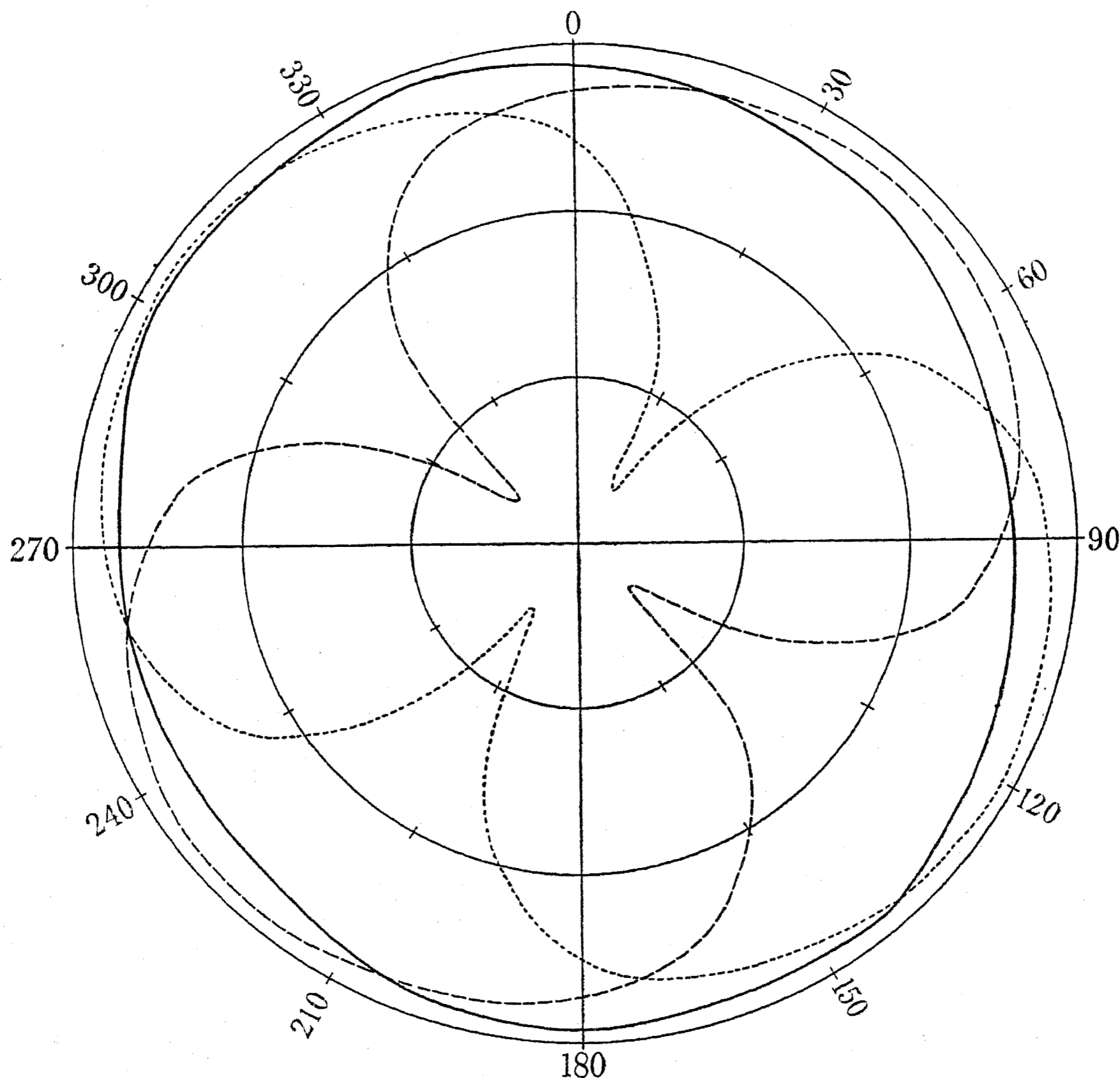


FIG. 18.—Output from phasing receiver on 5XX.

— Curve of one frame coil only.
 - - - Curve of other frame coil.
 ——— Curve of two frame coils together.

tion factor of each of the valves V_1 and V_2 , assumed to be identical.

The voltage between the points M, N, i.e. across C_3 , is given by

$$e'_1 = \frac{i_1}{jpC_3} = \frac{1}{jpC_3} \cdot \frac{\mu F_1 \sin \theta e^{jpt}}{(R_a + R_1) + \frac{1}{jpC_1} + \frac{1}{jpC_3}} \quad (32)$$

and that between P and N, i.e. across R_2 , is given by

$$e'_2 = R_2 i_2 = R_2 \frac{\mu F_1 \cos \theta e^{jpt}}{R_a + R_2 + \frac{1}{jpC_2} + \frac{1}{jpC_4}} \quad (33)$$

phase by $\pi/2$. Hence, if the valves V_3 and V_4 are identical, the currents produced in their common output circuit will be of the form given in equation (29) and the resultant amplitude will be independent of the angle θ in magnitude.

In practice it is not convenient to make either C_3 and C_4 or R_1 and R_2 variable, in order to make $R_2 = 1/(pC_3)$ for all values of p . These are therefore fixed for the mean frequency of the band to be covered, and an amplitude adjustment is made at any other frequency by varying the anode voltage on the valves V_3 and V_4 by means of the potentiometer $R_9 R_{10}$.

Convenient values for frequencies around 200 kilo-

cycles per second are: $C_1 = C_2 = 0.020 \mu\text{F}$, $C_3 = C_4 = 0.001 \mu\text{F}$, $R_1 = R_2 = 1\,000$ ohms.

A curve showing the output from this device when followed by a high-frequency amplifier, detector, and note magnifier, using the carrier wave of 5XX as an incoming signal, is shown in Fig. 18 for a rotation of 360° of the frame-coil system about a vertical axis. The dotted curves show the response of the receiver for the two frames independently, whilst the full-line curve shows the response with the two frames together. The ordinates are the readings obtained with a Moullin voltmeter behind the note magnifier, and are therefore approximately proportional to the square of the voltage applied to the detector valve, so that for the voltage applied to the detector the departure from a circle would be less than that shown in the diagram.

(4) RECEIVER POWER SUPPLIES.

In the majority of ships the anode and filament voltages for all the receivers in an office are supplied from a common 100-volt battery and a common 4-volt battery fitted outside the actual silent compartment, in a steel battery cupboard. From the battery cupboard four leads are run to a battery distributing board inside the office. At this board, positive L.T. and negative H.T. are joined together, and from the board (which contains the battery switches) three leads are run to each receiving bay. The negative L.T. lead is earthed at the distributing board, via a pea lamp, which functions (a) as an earth and (b) as a fuse in the event of an earth fault developing on the positive H.T. lead. In order to prevent back coupling between various receivers via the H.T. battery, a cushioning unit is fitted in each receiving bay between the distributing board and the models. This is of conventional type, made up with chokes and condensers.

Where a large number of receivers are to be run from a common source of supply a battery has many advantages, for it gives an almost constant voltage and its internal resistance is very low. Within limits the voltage is almost independent of the load, whilst back coupling between receivers is small. These points are both of great importance in naval reception, especially the first one, since various receivers are liable to be switched on and off at short notice. The great disadvantages of battery supplies are: (a) The weight and space required by the batteries and charging equipment. (b) The difficulties and cost of upkeep, and the cost of replacement, particularly of the small cells in hot climates.

Under modern conditions in ships these two factors are so important that, as was mentioned by Mr. G. Shearing in his recent Address,* various types of generator supplies have been tried out and a system of a.c. supply has been adopted in some special cases. At first sight it might appear that the problem had already been solved by manufacturers of eliminators, but trials showed that this was far from being the case. The difficulties of designing a single receiver to work from a.c. supplies and using indirectly heated valves, are not enormous, though they are worse than might be anticipated. Under naval conditions it is necessary to start with a signal of the order of a few microvolts per metre only

and amplify this sufficiently to receive at good strength in telephones, and it is well known that the ratio of hum to signal must be much smaller for telephone reception than it need be for loud-speaker reception. The major part of the problem is, however, connected with two other factors. The first of these is that of supplies to old receivers (some of them 10 years old) which were designed to work with battery valves and use 4 volts on the filaments and 50 volts on the anodes. These receivers contain no decoupling devices. The second is that of regulation. Naval ships are not in general fitted with alternators, and hence a separate small motor-alternator is necessary to supply alternating current to the office. It then becomes necessary to fit automatic control gear to overcome the difficulties of regulation which naturally arise from (a) variations of input voltage,

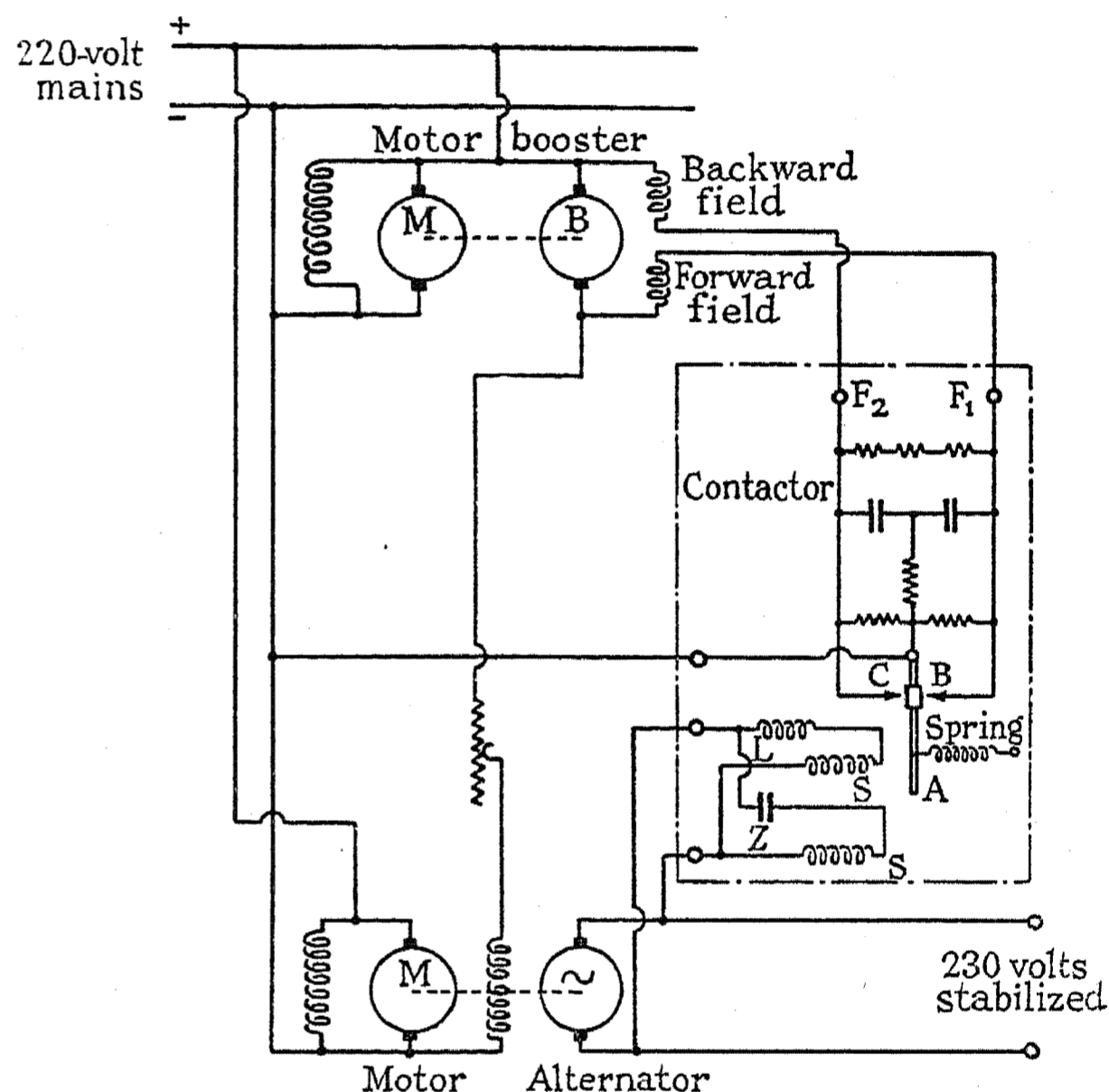


FIG. 19.—Wiring of booster, contactor, and motor-alternator.

which are liable to be quite large; and (b) variations of output load, which may be of the order of 10 to 1.

The apparatus developed consists of an alternating-current contactor and a reversing booster working on the alternator field. The wiring diagram of the booster contactor, and alternator, is shown in Fig. 19. As will be seen from the diagram, the output voltage of the alternator controls the contactor, whilst the contactor in turn controls the alternator field via the booster. If the alternator output rises, the armature A is pulled over by the solenoid S and makes contact with C; the backward field F_2 of the booster is energized and the forward field F_1 open-circuited; hence the booster reduces the alternator field current and the a.c. output voltage falls. When this voltage has fallen below the predetermined value, a spring pulls the armature A over to the contact B; the backward field F_2 is now open-circuited, the forward field F_1 energized, and the booster increases the alternator field-current. In practice, therefore, the armature A is always vibrating between the contacts C and B. The various resistances and condensers in the contactor are necessary to prevent surges and sparking.

* *Journal I.E.E.*, 1934, vol. 74, p. 11.

The solenoid S has two windings, each fed separately from the output of the alternator. In series with one winding there is a condenser Z, and in series with the other an inductance L. This arrangement is provided to compensate for the change in frequency which must occur when the alternator is running slowly owing to low input voltage to the motor, or quickly owing to a rise in input voltage. To test the working of the control system, a series of oscillograms were taken on a 3-kW 500-cycle alternator. The machine was loaded up to full capacity by a resistance, which could be thrown on

a modified booster and contactor to give quicker action. Fig. 23 shows the effect of throwing the load on and off the alternator with the voltage control in action, and Fig. 24 without voltage control. When the load is thrown off, there is an abrupt voltage-rise of about 50 per cent for this machine, but the voltage is brought back to normal in about 0.2 sec., whilst when the load is put on there is a very similar drop which is compensated in about the same period of time. Calculation shows that even if the load were thrown on and off 5 times every second (a most unlikely condition) the

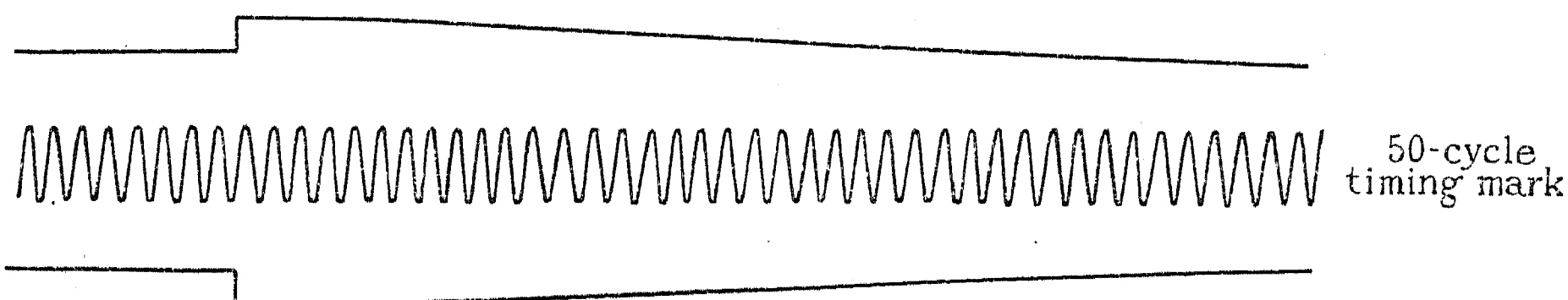


FIG. 20.—Effect on output voltage of switching off full load (3-kW machine).

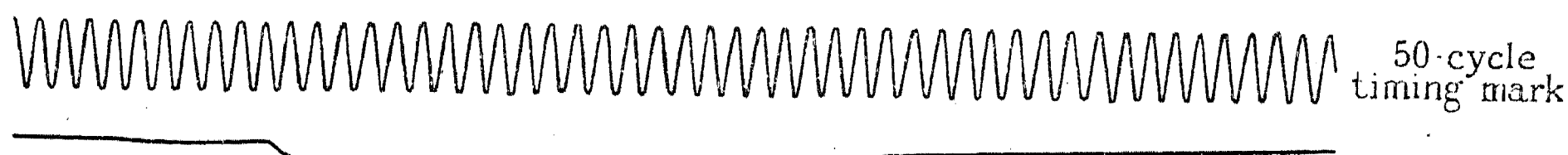


FIG. 21.—Effect on filament voltage of switching off full load (3-kW machine).

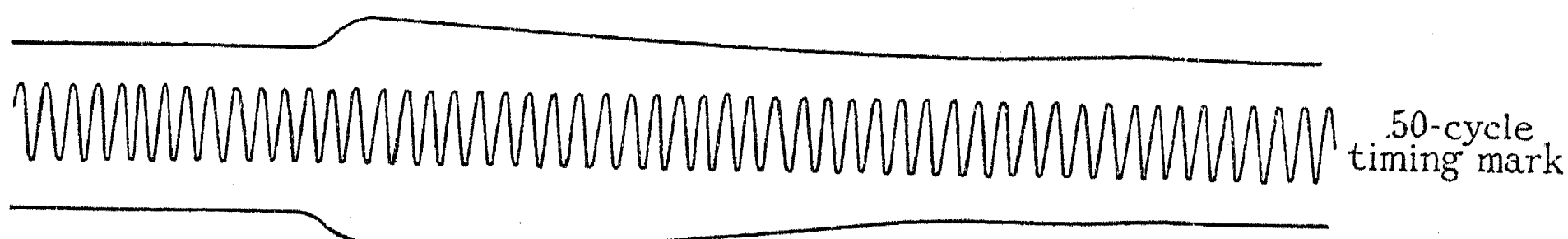


FIG. 22.—Effect on anode and filament currents of switching off full load (3-kW machine).

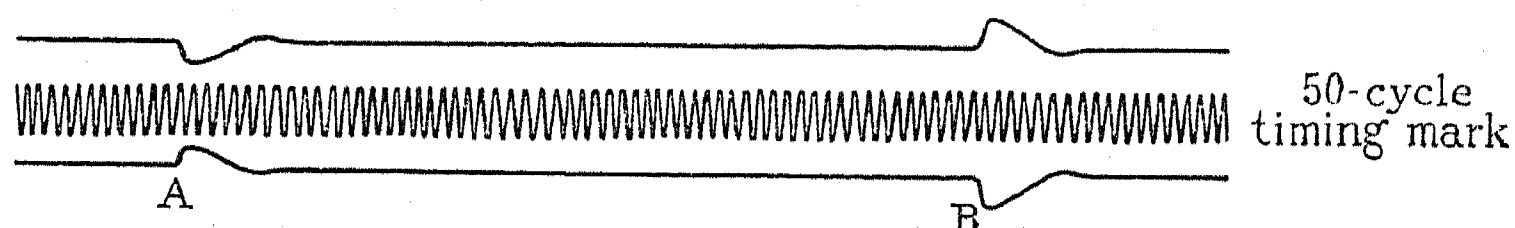


FIG. 23.—Oscillogram showing effect on output voltage of switching full load on and off. Quick-acting booster in operation.

and off by means of a quick-break magnetically-controlled switch. In addition to this resistance load, a rectifier and filter system suitable for supplying the anode and filament voltages to a receiver (see Figs. 25 and 26) was wired straight across the alternator terminals. The load due to the rectifier system was only a few watts; hence its effect on the machine regulation was negligible, and therefore throwing the resistance load on and off tests the regulation of the machine from full load to no load. Fig. 20 shows the variation of output voltage of the machine when full load is suddenly thrown off. As will be seen, the output voltage rises suddenly by about 30 per cent in less than 0.02 sec. and is then brought back to normal by the booster in a little over 0.5 sec. Owing to the smoothing action of the filters and thermal delay in the valve filaments, the rise in filament voltage and anode and filament currents is less abrupt, as shown in Figs. 21 and 22. The oscillograms shown in Figs. 23 and 24 are for a similar machine, but with

heat generated in the valve filaments, calculated as E^2/R , would only be increased by about 8 per cent above the normal value; hence no damage would be done to the filament emission.

The effects of variation of input voltage are less

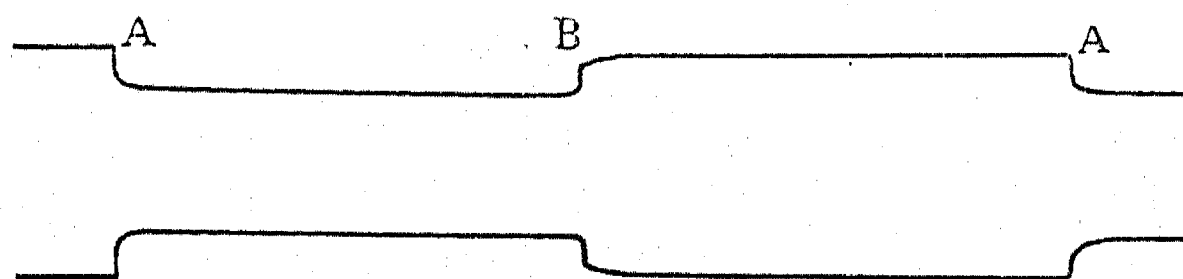


FIG. 24.—Booster not in operation.

serious than those of load, since the inertia of the machines makes all changes less sudden and the booster correction therefore appears relatively more rapid.

The complete wiring diagram for the supply of one bay of the receiving room is shown in Fig. 25 and calls for little comment as regards circuit details, since the

rectifiers, chokes, condensers, etc., are all of conventional type. For a 50-cycle a.c. supply no unforeseen difficulties arise, but in certain cases it is necessary to use an existing 500-cycle alternator as source of supply, when considerable difficulty is encountered. In the first place the human ear is exceedingly sensitive to notes of frequency 500 to 1 000 cycles per sec.; secondly, the low-frequency stages of the amplifiers are purposely designed to give full amplification for frequencies within this band. Hence the order of smoothing required is

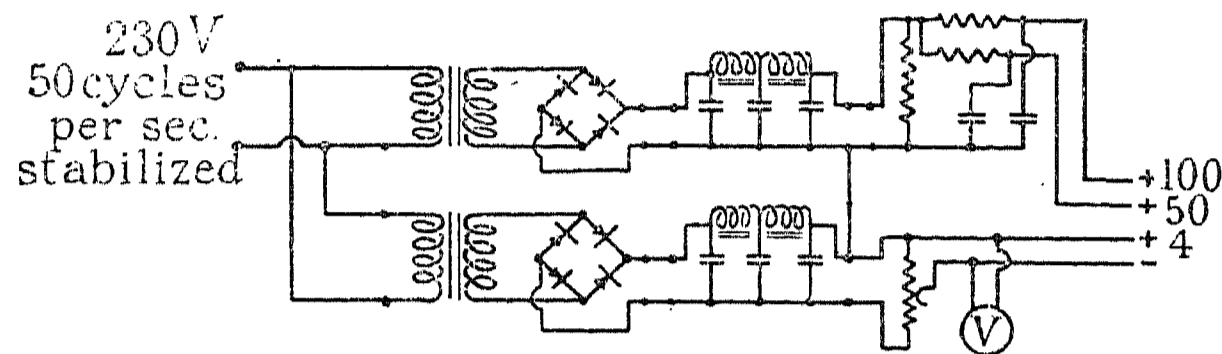


FIG. 25.—Rectifier system for single bay.

very much greater on 500 than on 50 cycles per sec. This is partly compensated by the fact that for the same chokes and condensers the impedance of each choke is 10 times as great and the impedance of each condenser one-tenth. Experience shows, however, that this compensation is not in itself enough, and the filters have to be improved by screening the transformers and chokes separately in iron cases to prevent pick-up by induction from one stage of the filter to the next. It is also necessary to modify the wiring of the filament filter as shown in Fig. 26, otherwise coupling is developed by the resistance of the wiring in the filter. With these modifications, hum is eliminated in low- and medium-frequency receivers, even when using three stages of

note magnification. In high-frequency receivers, however, using an oscillating detector valve, a phenomenon arises which is called "tuneable hum" for want of a better name. In this case a 500-cycle note tunes in at various places on the range of the receiver, like a series of harmonics. It can, however, be eliminated by fitting a radio-frequency filter in the filament-leads. The explanation of this effect is not very obvious; but it is possible that the filament leads tune for certain isolated frequencies and that the oscillation in the leads is then modulated by the ripple from the rectifier. Fitting the

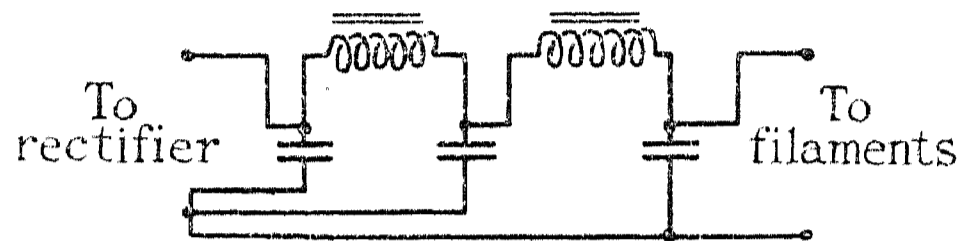


FIG. 26.—Low-frequency filament filter.

radio-frequency filter renders them more or less non-reflective and prevents the oscillation from building up.

Although the question of supplies is not yet finally settled, it is probable that in the near future batteries will be replaced by a 50-cycle motor-alternator.

In conclusion, the author wishes to express his thanks to the Board of Admiralty for permission to publish this paper; to the Captain, H.M. Signal School, for facilities afforded in its preparation; to his colleagues in the Receiving Section, especially Mr. L. S. Alder, M.Sc.; and finally to Mr. G. Shearing, O.B.E., B.Sc., Member, who, as Director of the Experimental Division, has given much assistance by his technical advice and criticism.

DISCUSSION BEFORE THE WIRELESS SECTION, 7TH MARCH, 1934.

Captain A. J. L. Murray: I should like to emphasize that the designer at H.M. Signal School is greatly handicapped by the conditions imposed on him. He is under the necessity of keeping the weight within reasonable limits, though fortunately not the narrow limits within which the Royal Air Force have to work, and he has to design the equipment so that it will fit into a small space. Further, he has to consider how it will stand up to concussion caused by gunfire, which incidentally may raise the noise level! Hitherto the Navy has not used radio-telephony because of its obvious disadvantages of lack of secrecy, liability to phonetic errors, and the fact that as compared with morse it does not save time. It must also be borne in mind that we have to deal in many cases with very young and inexperienced operators. The Navy has a large number of boy telegraphists who have just gone to sea, and who have to be given training. They cannot be trained in the schoolroom; they must be put to keep watch on Service wavelengths. For this reason the equipment must be foolproof. Not only have we to pick out between 5 and 15 different transmitting ships, which may be transmitting on slightly different adjustments one after the other, in answer to the admiral's signals, but we also have to be able to change the wavelength practically instantaneously under certain circumstances. An important factor in naval work is the long life which

we have to expect from our receivers. There may be 200 to 400 receivers of one type—say, the medium-frequency receiver—in service. When a new type is introduced all these have to be scrapped, and we cannot afford to do this unless the new type is a very great advance on the old.

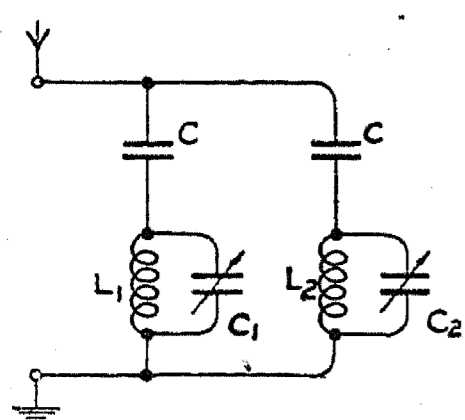
Mr. S. B. Smith: The difference between naval and mercantile-marine wireless is very great, owing to obvious naval limitations. The author's work is seriously hampered in that wireless problems cannot always be solved from a technical point of view. The losses experienced in feeding the main aerials via paper cables to the various receiving sets place a practical limit to the field intensities on which good reception is possible. In the case of naval reception it is assumed that in most cases the limit of readability is not imposed by valve noise but by radio noise, caused either by jamming or by ship noise. In medium-wave aperiodic Adcock direction-finding systems it has been my experience that, provided the aerials, feeders, and transformers, are carefully designed, the minimum field-intensity levels on which reception is possible (assuming a quiet site) are determined by radio noise and not by valve noise. It would be of interest if the author would give some figures of the ship-noise levels on various wavelengths. R. K. Potter* and other

* *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 1512.

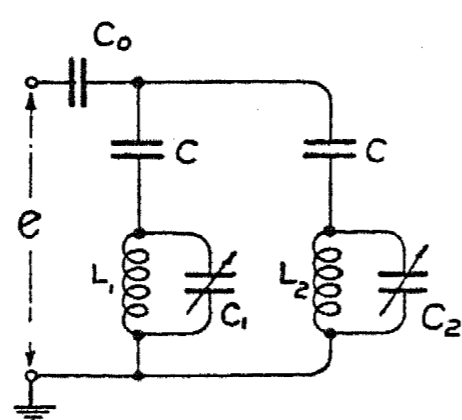
workers have produced noise charts, and further study in this direction will be well repaid. It is well known that man-made static, such as ship noise, can be reduced by using elevated horizontal dipoles for short-wave reception. Is the application of such aerials to H.M. ships quite out of the question? With regard to the sensitivity of simple short-wave receivers, the Marconi Company find that receivers such as that illustrated in Fig. 5 will give an R5 Washington signal (assumed equivalent to 10 decibels below 1 milliwatt) on fields of the order of 0.4 microvolt per metre below 20 metres, and 0.1 microvolt per metre above that wavelength. On the medium-frequency receivers, such as that shown in Fig. 8, the field intensity for an R5 signal will vary from 0.1 microvolt per metre on the shortest wavelength up to 8 microvolts per metre on the longest wavelength. On low-frequency receivers, the sensitivity will vary from 1 microvolt per metre to a maximum of 35 microvolts per metre on a wavelength of 20 000 metres. With regard to telegraphic selectivity, the medium-frequency and low-frequency selectivity is determined by the low-frequency tuning. The signal-frequency selectivity of most naval receivers is only capable of reducing image-signal jamming. The aperiodic coupling valve

system is applied to the reception of a band of frequencies, it seems to me that a slight misphasing of the loop condensers will provide directional discrimination inherent in loop reception. I should like to ask the author whether the two pairs of loops and condensers are matched and ganged in order to avoid this operating defect.

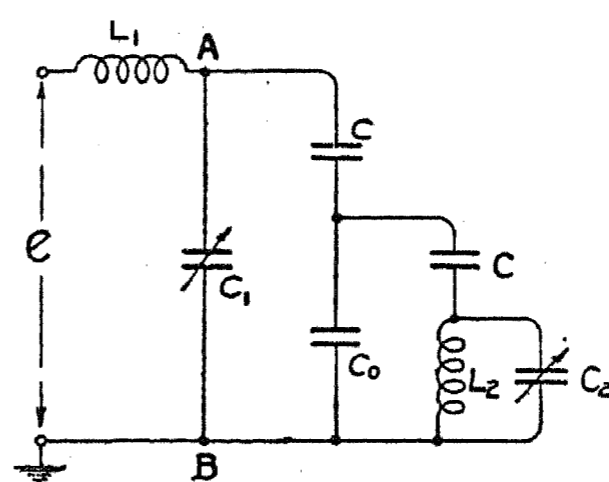
Mr. M. Reed: Many of the problems and difficulties discussed in the paper are also encountered in mercantile ships, and it may therefore be of interest to refer to two or three arrangements which are employed in such ships to satisfy requirements similar to those given in the paper. The first of these concerns the problem, raised on page 298, of connecting more than one receiver to the same aerial. We have found that it is possible to operate as many as 5 receivers from the same aerial without introducing appreciable mutual interference, provided that each receiver is coupled to the aerial by a condenser of low capacitance. A suitable value for this condenser can be determined by considering the arrangement shown in Fig. A. For convenience it is assumed that only two receivers are connected to the same aerial, and that L_1 , C_1 , and L_2 , C_2 , respectively, represent the first tuned circuit of each receiver. These



(a)



(b)



(c)

$$C_{eff.} = C_1 + \frac{C}{1 + \frac{C}{C_0 + \frac{C}{1 + \frac{C}{C_2 - 1/(\omega^2 L_2)}}}}$$

FIG. A.

employed in several types of naval receivers does not allow good duplexing unless very careful wavelength organizations are chosen. The cross modulation experienced under duplex conditions will wipe out the amplifier acting as a superheterodyne receiver. By using a suitable phasing resistance connected in both grid and plate circuits of the coupling valve, it is possible to provide greatly improved cross-modulation protection. Needless to say, the gain of the stage will be reduced when working in this condition. Tests carried out at Chelmsford have shown that with two signals—both of 0.5 volt—sweeping a cardioid valve grid, and the receiver tuned to the beat, the voice-frequency output of the receiver is about 2 volts across a 600-ohm resistance. By inserting a compensating resistance and adjusting the receiver to the same overall gain, the output was reduced by 80 decibels below the previous figure. This type of aperiodic compensation is not possible on short waves, but is excellent on medium and long waves. It has made coupling-wave technique much more immune from beat effects. Of course, the balance is not sufficiently good to allow of duplex working on a common transmitting and receiving aerial. With regard to quadrature combination of two loop aerials for the purpose of avoiding directional effects, methods of this type are well known in beacon practice. When this

circuits are coupled to the aerial by means of the condensers C . In (b), diagram (a) is redrawn on the assumption that the capacitance of the aerial can be represented by C_0 , its inductance and resistance being neglected. To estimate the effect of varying L_2 , C_2 , on the first receiver, when it is tuned to receive signals of frequency $\omega/(2\pi)$, we can convert (b) into (c) by making use of a theorem, due to Moullin,* that the resonance condition of a system remains unchanged when the input terminals are short-circuited and the source is placed in any series or shunt member. From (c), the value of the effective capacitance which tunes L_1 can easily be shown to be given by the expression for $C_{eff.}$. This expression shows that, provided the second receiver is not tuned to frequencies in the neighbourhood of those to which the first receiver is tuned, variation of C_2 will have practically no influence on the value of $C_{eff.}$ if C is kept reasonably small. We have found that satisfactory results are obtained when the capacitance of the coupling condenser for each receiver is made equal to the minimum capacitance of the respective tuning condenser. My second point concerns an arrangement for controlling the selectivity of a note filter of the type shown in Fig. 14. We have found that this can be easily accomplished if the tuned circuit is coupled to the

* *Proceedings of the Cambridge Philosophical Society*, 1926, vol. 23, p. 391.

plate of the valve by means of a condenser C_1 in the way shown in diagram (a), Fig. B. This circuit is redrawn in (b), where R_1 represents the plate-filament impedance. Diagram (c) shows curves relating the selectivity factor and the amplification factor of such a system with x , a quantity which is defined by the equation

$$x = \frac{C_1 \sqrt{(R_1/R)}}{C + C_1}$$

For a given valve and tuned circuit, x depends only on the value of C_1 . By making C_1 variable it is easy to

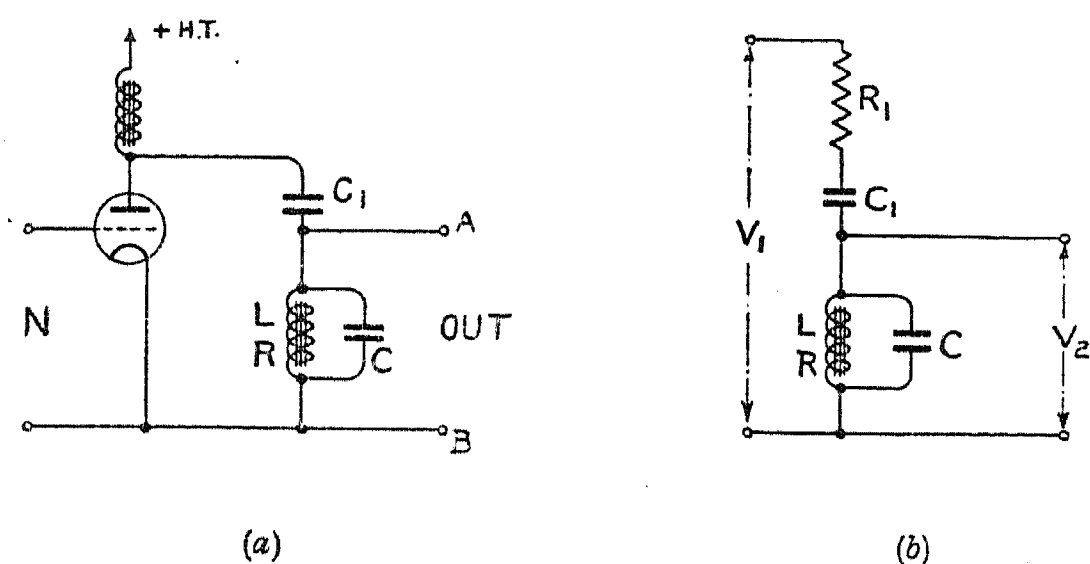


FIG. B.

adapt the filter to any required condition. My final point concerns the problem, discussed on page 306, of obtaining smooth reaction over a frequency range of 15 to 20 000 kilocycles per sec. To do this we employ the arrangement shown in Fig. C, in which reaction of the Reinartz type is used from 20 000 to 100 kilocycles per sec., the magnetic coupling between L_3 and L_4 being fixed and the condenser C variable. From 100 to 15 kilo-

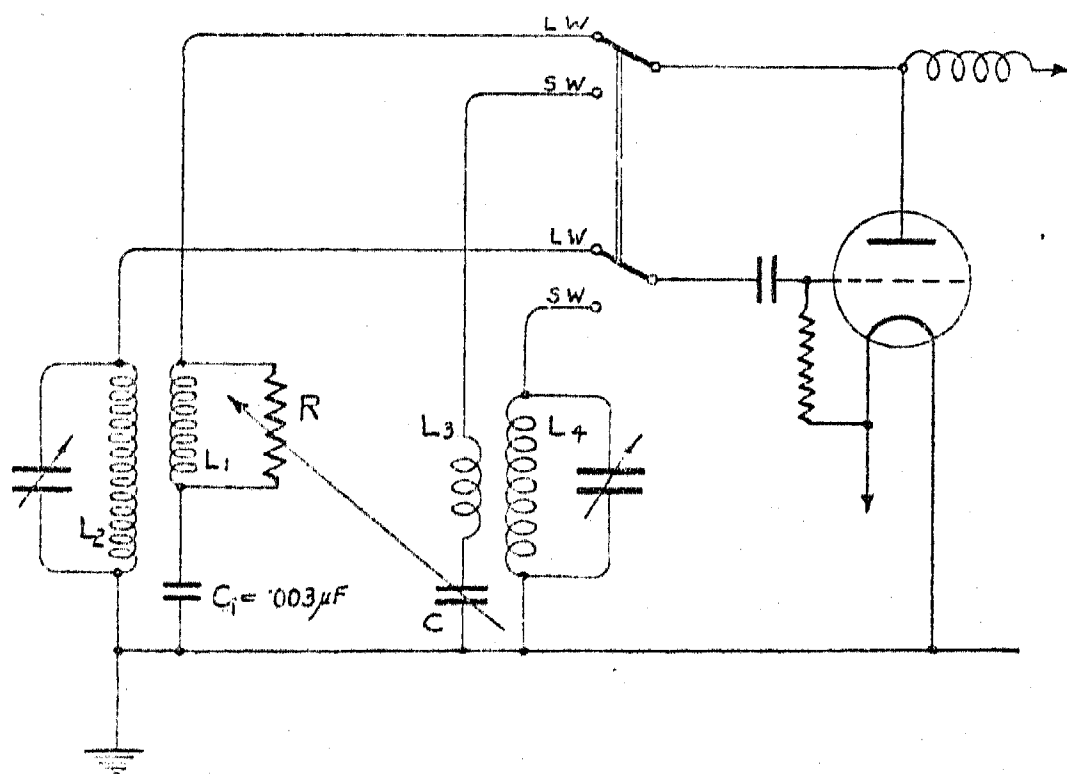


FIG. C.

cycles per sec. a modified form of the Reinartz type of reaction is employed, the condenser C_1 now being fixed and the magnetic coupling between L_1 and L_2 varied by means of the resistance R . The condenser C and the resistance R are ganged on the same spindle, so that the operator has only one control to manipulate. The above arrangement enables smooth reaction over the frequency range 100–15 kilocycles per sec. to be obtained with a single coil for L_1 .

Mr. R. W. Minter: In my opinion there might well be some change in the attitude of the powers that be in regard to the disposition of the wireless office on board

naval ships. In his recent Address* Mr. Shearing included a diagram showing the main wireless office under the mainmast and the second office well back on the quarter-deck. From the point of view of noise, however, one would have expected the main office to have been placed in the position occupied by the second office. There is seldom any necessity to use the main aerial for receiving, except in large cruisers, because the subsidiary aerials are capable of performing the service quite well; it therefore seems to me that, for the receiving office at any rate, a position might be found under the

quarter-deck. I should like to know whether the question of providing an aerial trunk has been discussed; perhaps this might be considered in relation to the position of the wireless office. With regard to the use of cross-loops, following Prof. Artom's investigations, would not the addition of a goniometer be a great advantage and cut out jamming? There would be an added advantage in the reception by the cross-loop in the event of the whole upper structure being shot away. The early part of the paper mentions the proper shielding of each component, a matter to which the designers of broadcast receivers do not give sufficient attention. I am surprised to see, in connection with Fig. 6, the reference to the plug-in coils for receiving. I should like to know whether it is possible to keep to programme when the wrong coil is put in. A little later in the paper the discrepancies of the tuning of the medium-frequency receiver are referred to, and the slide which the author showed leads me to think that the device he proposes is too complicated to be used by the junior ratings. I should like to ask whether some simplification is not possible. In naval signalling the wireless-telegraph signallers seem, by comparison with the mercantile-marine operators, to be slow. Is this due to the conditions in the office where the signalling goes on, or to some internal conditions affecting the stability of the heterodyne? I agree with the author that the problem of hum in receivers is by no means solved; it seems to me, from my experience in a listening capacity, to be getting more acute in some cases. I notice the author's reference, in connection with the stand-by receiver, to the six fixed coils which are connected to the 6-way switch and cover the low-frequency range. This offers a good contrast to the plug-in coils mentioned earlier in the paper. Could not such a switch arrangement be applied instead of the plug-in coil system?

* *Journal I.E.E.*, 1934, vol. 74, p. 11.

Mr. F. S. Barton: It has been my privilege to inspect the central receiving room of a modern naval ship equipped with the receivers described in the paper; the whole installation presents a very workmanlike appearance and seems to be suited to the type of communication required. I should like to ask the author for some data with regard to the coils he uses, particularly the slot-wound coils. Perhaps in his description of them he would incorporate some data as to the magnification. I am interested to notice that it is the practice to vary the audio-frequency gain of the receiver by switching the complete stage. Is there any special reason for this system? It seems to me that the usual volume control might be simpler and more convenient. In view of other speakers' remarks as to the reaction control on the stand-by receiver, I would mention that my own experience of it has shown it to be very smooth and convenient over the whole range.

Dr. L. E. C. Hughes: I have found that radio-frequency currents can be readily transmitted along conductors in ordinary lead sheaths without undue loss for several hundred feet. In a particular instance a frequency of about 1 million cycles per sec. was efficiently modulated by a condenser transmitter at the end of a long cable, the circuits at each end being series-tuned. In the present instance a very wide frequency band must be allowed for, and it seems possible that suitable transformers at the ends of the cable, having the correct ratio and very tight coupling, would convert it into a correctly terminated transmission line. A transformer with a toroid dust-core might give adequate coupling over the desired frequency range.

Mr. L. B. Turner: The author distinguishes between two types of interference. In the one, with which broadcasters are familiar, the interfering signal is weak and at a slightly different frequency; in the other, met in naval practice, it is strong and at a very different frequency. For the latter, he says, "the so-called highly selective receiver, embodying a single tuned circuit of very low decrement, does not prove in practice to be the receiver of greatest selectivity"; and he gives an analysis showing that for naval purposes two circuits of moderate decrement are better than one of very low decrement. I wish to point out that the same conclusion holds with reference to the former type of interference. I am interested in the device (described on page 298 and elsewhere) by which one aperiodic aerial circuit is capable of exciting any number of tuned receivers without mutual interaction. Twelve years ago I was granted a patent (No. 189693) for that precise device, which is very simple, obvious, and effective. I allowed the patent to lapse, but I am gratified to find that about two-thirds of the receivers in the Navy now embody this device.

Commander J. A. Slee: Even in the early days of naval wireless communication we were struggling with one of the difficulties mentioned by the author, namely that of receiving weak signals through strong signals. We found that it was essential to use well-made and well-designed apparatus incorporating many tuned circuits. We had to make them of low resistance and high insulation, and the penalty we had to pay for efficiency was the difficulty in using them. The signal

officers had first to become accustomed to using them themselves, and then they had to train the men. It was on the signal officers that success depended. We also were faced with the problem of multiple reception on several wavelengths on one ship in the face of strong interference, which might be deliberate. I am interested in the use of one aerial, when necessary, for many receptions. I remember the early beginnings of multiple reception, when we achieved first two and then three receptions on the same aerial. We found then that we got better results if we had, not three receivers for one aerial, but three aeriels and one receiver to each. A particularly annoying and difficult problem used to be encountered when it was necessary for a ship to receive a weak distant signal while she was transmitting. Despite the fact that the frequency separation was great and the transmission of low power, with the apparatus then available the problem was very difficult.

Mr. A. J. Gill: In regard to the author's analysis of the aerial, we have exactly the same problem in broadcast reception where it is desired to avoid interference. Here we can sometimes put the aerial outside the zone of interference and connect it to the receiver by means of a screened lead. The difficulty is to get an arrangement such that the circuit is reasonably efficient within wide limits of tuning, and the author's analysis will be very useful in helping us to see what requirements have to be met. My second point relates to the author's tuning dials. I can testify to the excellence of the dials produced by the Admiralty. We have used a rather earlier design than that shown in the paper, and it has given us great satisfaction. A third point of interest relates to voltage control on the power supplies. Fig. 19 shows a motor-alternator and a motor booster, and I should like to ask the author whether he has considered the use of a Tirrill regulator on that alternator without the booster. The alternator has a resistance in the field circuit which is periodically short-circuited by a vibrator: I have had experience of it at Rugby on a 200-kW alternator supply, and have found that when controlled by a Tirrill regulator it functions very satisfactorily. If the whole of the output of the alternator is converted into direct current it is possible to by-pass this through a second winding on the alternator field and bring up the voltage as the load comes on. This was actually done by the Post Office at Portishead on a short-wave transmitter working as a self-oscillator without master control, where for frequency stability it was essential to maintain a steady voltage on the anode and filament supplies. The alternator was provided with two field windings; one was normally excited and the other carried the rectified anode current in series with the anode-filament circuit of the oscillator. Thus, as soon as the load was put on, the anode current increased the alternator field and maintained the voltage at the normal value. It was possible by adjustment of a resistance across the second winding to keep the voltage absolutely steady, or even to make it rise on load. Other methods are now available for regulating these voltages by means of grid-controlled mercury-vapour rectifiers, or thyatrons, which also enable one to dispense with vibrating contacts.

Mr. L. H. Bainbridge-Bell: The crossed-coil receiver,

the circuit of which is shown in Fig. 17, is somewhat similar to that used by Ratcliffe and White at Cambridge, and also by T. L. Eckersley, to determine the sense of rotation of circularly-polarized components of waves reflected from the ionosphere. Under certain conditions it might happen that only one circularly-polarized component might arrive at the receiver. In this case (depending on the sense of winding of the coils and of their connection to the receiver) the resultant received signal might be zero. Has the author noticed any effect of this nature, and, if so, has he tried inserting a reversing switch in one of the circuits and observing the strength of received signal with the switch in its two positions?

Dr. E. H. Rayner: I should like to ask the author whether he has considered the methods of voltage regulation developed during the last few years in connection with motor transport. The vibrating type of regulator is apparently very successful commercially and is practically foolproof; it is now used largely on motor-omnibuses and lorries. This method of voltage regulation is a good deal simpler than the one suggested in the paper, and it might be of use in naval wireless reception. I believe that general vibration may assist satisfactory operation of this type of apparatus.

Mr. R. A. Watson Watt: I should like to take up a remark of Mr. Bainbridge-Bell and to add that there is another potential advantage in the crossed-coil receiver shown in Fig. 19. In certain cases an arrangement of that sort may be a useful anti-fading device. I have in mind cases where phase fading is taking place between the two oppositely polarized components of the signal. The elimination of one of these components may leave an amplitude steadier than that of the combined signal.

Mr. H. G. M. Spratt: I too should like to raise a point in connection with the regulation. It seems to me that there is no reason why the alternator should not have a compound winding, fed from the armature current of the motor. There is a possibility that under these circumstances the regulation over the whole range from full load to no load would not be sufficiently good, or, alternatively, that the time of recovery on a sudden change of load would not be quite as short as in the case of the motor booster. I should be glad if the author would enlighten me on this point.

Dr. W. F. Rawlinson (*in reply*): Captain Murray's remarks bring out very clearly the conditions under which reception of wireless signals must be carried out in a man-of-war. These conditions have a great influence on the types of receivers which can be fitted and on the constructional details of these receivers, and they often present problems more difficult of solution than the actual technical considerations.

I agree with Mr. Smith that in almost all cases the limit of readability is due to interference reaching the receiver either via the aerial or via the receiver supply leads, and is not due to valve noise. No actual measurements have been made of ship-noise level, but aural observations show that the noise level varies enormously from ship to ship and also in the same ship at different times. The best estimate of noise level can perhaps be obtained from the statement that on medium-frequency receivers it is usually necessary to have available a field strength of the order of 20 microvolts

per metre to provide successful working. The use of elevated dipoles for short-wave reception is generally ruled out owing to proximity to the main aerial and difficulty of running a feeder amidships. As regards the sensitivity figures given, that for the receiver illustrated in Fig. 5 for wavelengths below 20 metres is too high. Only one stage of high-frequency amplification is used, and a field strength of the order of 5 microvolts per metre would be more nearly correct. Above 50 metres, where two stages of high-frequency amplification are used, the figure of 0.1 microvolt per metre agrees with measurements. For the medium- and low-frequency receivers the average figure is about 4 microvolts per metre. It should be noted, however, that under ship conditions field strengths of these minimum values would not be sufficient owing to the radio-frequency noise level. An idea of the signal-frequency selectivity of the low-frequency receiver can be obtained from the fact that on a frequency of 30 kilocycles per sec. the image signal is reduced by from 50 to 60 decibels. The method suggested for cross-modulation protection is of interest. In the phasing receiver shown in Fig. 17 it is true that a misphasing of the loop condensers will produce maxima and minima, but provided the minima are not sharp zeros they will not lead to the missing of a signal. The coils and condensers are matched, but not ganged.

Mr. Reed puts forward an alternative method of connecting several receivers to one aerial. This method of using small coupling condensers was actually considered and tried. It was abandoned for the reason that it is at times necessary to tune one receiver close to, or even through, the tuning of another, when interaction between the receivers becomes evident. In addition, the tuning of the receiver is no longer independent of the size of the aerial, unless the coupling condensers are very small. The method described of adjusting the selectivity of a circuit is very simple, but it suffers from the disadvantage that when the selectivity is a maximum the amplification is zero. The problem of providing smooth reaction over a very large range of frequencies is a difficult one. A solution has been found in the circuit shown in Fig. 15, but it is interesting to note from Mr. Reed's remarks that there is at least one alternative to this.

With reference to the point raised by Mr. Minter, in a naval ship many factors have to be taken into consideration, and the positions of offices and the running of aerial trunks cannot be decided from the point of view of wireless efficiency alone. A goniometer could be used with the crossed-loop receiver, but would add to the expense and complication. It is pointed out that plug-in coils are used in the high-frequency receiver and also in the stand-by receiver when working on high frequencies. Switching is avoided, because experience has shown that it gives rise to stray coupling and excessive damping. As regards the question of the speed of naval signalling, first-time accuracy in both transmission and reception is essential. This is infinitely more important than mere key speed.

In reply to Mr. Barton, the magnification of the coils of the low-frequency tuner when contained in their metal screens is never less than 85 at any point on the tuning scale, and is considerably higher in many places.

The reason for switching the complete audio-frequency stage is the simplicity of this method. It requires only a single-pole switch, and this component is much less likely to give trouble than the usual types of volume control using resistances or potentiometers.

Dr. Hughes raises a point to which much consideration has been given, namely the possibility of converting the cable into a correctly terminated transmission line. Up to the present it has been impossible to design a transformer which will cover a wide band at high frequencies, but recent advances in the production of iron-cored toroids for radio frequencies suggest that the problem may not be impossible of solution.

It is gratifying to note that Mr. Turner agrees with the conclusions reached in the paper with regard to the question of selectivity of receivers for naval purposes.

The remarks of Commander Slee show very clearly that the reception of wireless signals in the Navy has always had its own particular difficulties, even from the earliest days. Experience amply confirms his opinion that the use of more than one receiver on an aerial is a necessary evil and that better results will always be

obtained if a separate aerial can be provided for each receiver.

Mr. Gill, Dr. Rayner, and Mr. Spratt, have all put forward alternative methods for controlling the output voltage of an alternator used to supply power to the anode and filament terminals of receivers. The method described in the paper, in which a motor-booster and contactor are used, is obviously not the only way of solving the problem. It has, however, given very satisfactory results in practice and is capable of meeting the two conditions which arise in H.M. ships, namely large variations in output load and sudden fluctuations in input voltage from the mains.

The points raised by Mr. Bainbridge-Bell and Mr. Watson Watt with regard to the crossed-coil receiver are very interesting. It was realized that this receiver might have uses other than that for which it was developed, and a few experiments were carried out with a similar receiver working on high frequencies. No evidence of the effect suggested by Mr. Bainbridge-Bell was obtained, but the receiver did show some promise as an anti-fading device.

CHARACTERISTICS OF TELEPHONE RECEIVERS.*

By W. WEST, B.A., Associate Member, and D. McMILLAN, B.Sc.

(Paper first received 4th October, and in revised form 15th November, 1933.)

SUMMARY.

Following a discussion of the acoustical load to which a telephone receiver is exposed when held to an ear, an account is given of measurements of the mechanical impedances of diaphragms. Since the measurements were made under circumstances for which the effects of the air on each side of the diaphragm were known, it has been possible to isolate the mechanical impedance of the diaphragm alone. Consequently modifications of the frequency characteristic of a receiver, resulting from known changes of the acoustical load, can be estimated. It is shown that the presence of the steady flux is responsible for most of the mechanical resistance of the diaphragm.

The magnetic forces by which the diaphragm is actuated have been studied by measurements of both the direct and alternating flux leaving the pole-pieces, and of the pull on the diaphragm due to the direct flux. Different diaphragms, spacing distances, and receivers, were used for these tests. It appears that, with the very adequate magnet strength used in modern receivers and the resultant degree of magnetic saturation of the diaphragm, the sensitivity of the receiver is not critical to variations either of magnet strength or of air-gap.

Typical examples of frequency characteristics of receivers, taken on an artificial ear, are shown, illustrating the effects of various simple modifications to the construction of the receiver. The sensitivity as recorded by the frequency characteristic of a receiver is in good agreement with that calculated from measurements of flux, pull, and mechanical impedance.

Some measurements are recorded of both amplitude distortion and non-linear distortion introduced by telephone receivers; the magnitudes are such as would not ordinarily be perceived by the ear.

(1) INTRODUCTION.

Although it is the oldest of telephone acoustical instruments, the telephone receiver has been subjected to little essential change in the process of evolution from its early days to the present time. Such change as there has been is mainly due to improvements in the quality of the materials which comprise the magnetic circuit, especially the permanent magnet and the diaphragm.

There has, however, been no lack of investigators to study the performance of the telephone receiver from different points of view. Prominent among these are Kennelly and his co-workers, whose researches have been collected in book form,[†] and also Mallett and Dutton.[‡] The study is, indeed, a fascinating one; it affords an

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† A. E. KENNELLY: "Electrical Vibration Instruments" (Macmillan Co., New York).

‡ E. MALLET and G. F. DUTTON: *Journal I.E.E.*, 1925, vol. 63, p. 502.

apparently simple link between the theory of vibrating systems and the practical realization.

From the practical point of view the investigations have, for the most part, suffered from the disadvantage that the experiments were made with the receiver operating in free air or under some other arbitrary acoustical condition, unrelated to the circumstances of actual use—namely, when the receiver is held to an ear. In order to carry out experiments with the receiver under its working conditions, there appear to be two alternative methods of procedure; either the insertion of a sound-pressure measuring device, small by comparison with the cavity of the outer ear, between the ear-cap and the ear; or by the use of a suitable arrangement for coupling the receiver to a sound-pressure measuring instrument, and at the same time exposing the receiver to an acoustical load which is similar to that of a normal ear.

The latter method has been employed at the Post Office Engineering Research Station, and in 1929 an "artificial ear" was designed for the purpose of studying or measuring the performance of receivers under their working conditions.

Since that time the artificial ear has been put to use for a number of different researches, some of which have involved also a study of the magnetic characteristics of the receivers tested. It is the purpose of the present paper to collect the results of these experiments into as connected a form as possible, and with a view to arriving at conclusions which are general rather than particular to the very limited number of types of receiver tested. For this reason frequent references to the underlying theory are desirable, even though, for the sake of simplicity, numerous approximations are made.

(2) TYPES OF TELEPHONE RECEIVERS INCLUDED IN THE INVESTIGATIONS.

Three types of telephone receiver only have been used to obtain the information recorded in this paper. These types are (a) the familiar Bell receiver, (b) the handset receiver, as used in this country in the new handset telephones, and (c) an ear-piece receiver, as supplied to Ordnance for use with a head-band. All the types are bi-polar receivers with parallel, rectangular pole-faces, operating a flat steel diaphragm which is clamped on by means of the ear-cap.

Certain dimensions and other particulars of interest are collected, for all three types of receivers, in Table 1.

The electrical impedance of a typical handset receiver, when held to an ear, is shown in Fig. 1.

TABLE 1.
Approximate Dimensions of three Types of Receiver.

	Bell receiver	Handset receiver	Ear-piece receiver
Diameter of diaphragm, in.	2.05	2.05	1.75
Diameter of clamping edge, in.	1.87	1.87	1.65
Depth of pole-faces below clamping surface, in.	0.0135	0.0135	0.011
Space between diaphragm and surface of ear-cap, in.	0.06	0.05	0.02
Number and diameter of aperture in ear-cap, in.	One 0.5	Seven each 0.1	One 0.5
Length of pole-face, in.	0.45	0.25	0.25
Width of pole-face, in.	0.075	0.1	0.06
Distance between centres of poles, in.	0.38	0.44	0.31
Volume of cavity behind diaphragm, cm ³	15	24	5.5
D.C. resistance, ohms	60	80	60

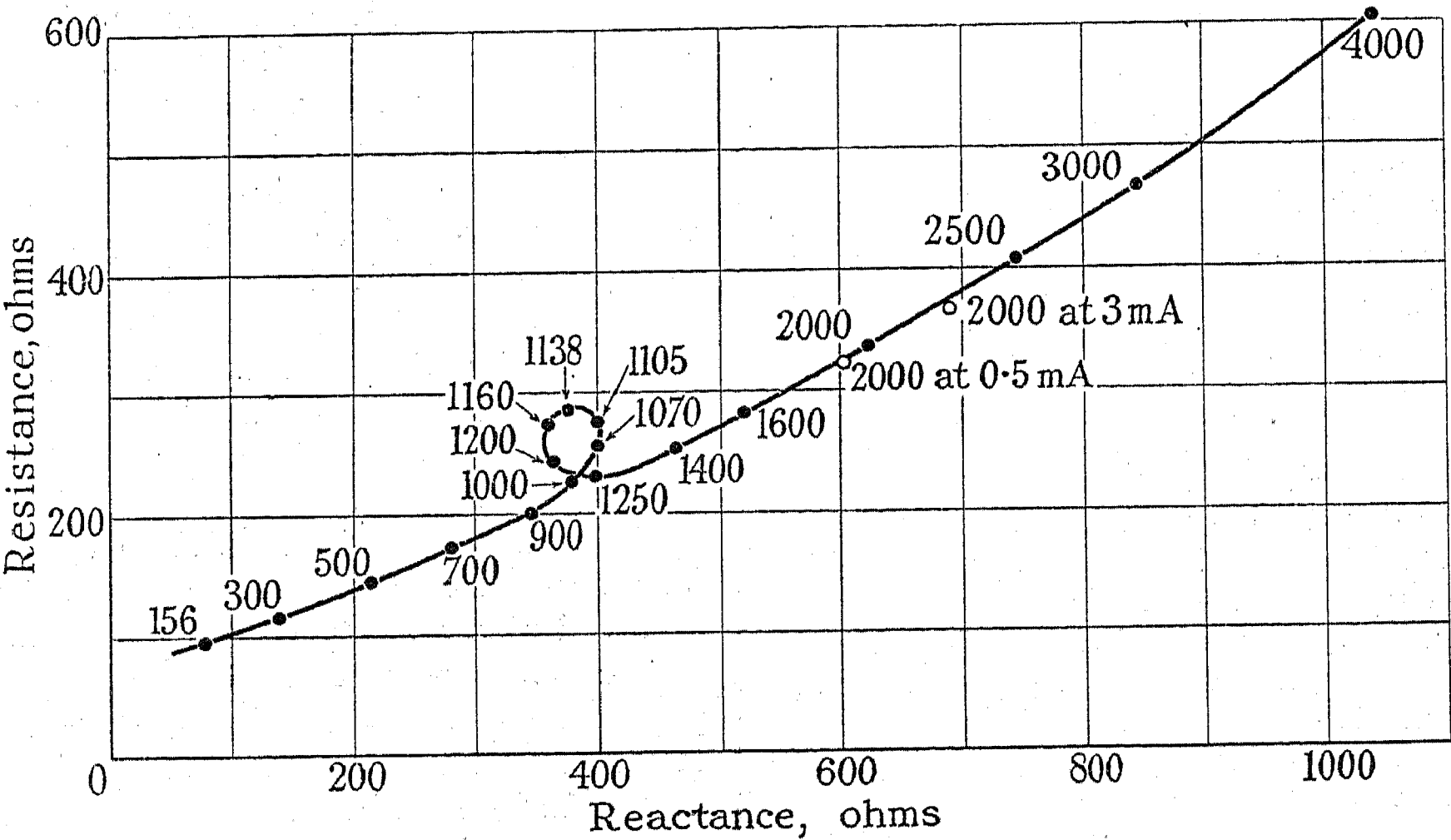


FIG. 1.—Electrical impedance of handset receiver; on artificial ear at 1 mA (frequencies in cycles per sec.).

TABLE 2.
Acoustical Load on Telephone Receiver when held to an Ear.

Frequency	12 normal ears		Artificial ear	
	Effective volume of cavity	Effective resistance area	Volume	Resistance area
cycles per sec.	cm ³	cm ²	cm ³	cm ²
350	—	0.14 to 0.4	—	0.39
500	— 4.0 to + 4.0	—	3.0	0.35
750	—	0.12 to 0.4	—	0.33
1 100	1.0 to 5.0	0.2 to 0.4	3.0	0.32
1 600	2.0 to 5.0	0.3 to 0.5	3.0	0.35
2 600	—	0.3 to 3.0	—	0.63

(3) THE ACOUSTICAL LOAD ON A TELEPHONE RECEIVER —ARTIFICIAL EARS.

Measurements of the acoustical impedance to which a receiver is exposed when held to the ear have been carried out at the Post Office Research Station* and also at the Bell Telephone Laboratories.† Variations between individual ears are, of course, considerable; variations with repeated tests on the same ear are also liable to occur when the manner of holding the receiver to the ear is not exactly repeated.

That somewhat wider variations were observed at the Bell Laboratories than at the Post Office Research Station may possibly be due to less restriction employed on the individual in the former tests as to the manner of holding the receiver to his ear. For the latter tests the subject was asked to maintain such pressure of the ear-cap on his ear as would be normal to him when listening to a "trunk call." This instruction was given in order to

tube, so terminated as to prevent reflection of sound from the farther end (to represent the resistance component). Near the cup a condenser transmitter was so mounted that the diaphragm would be actuated by sound passing along the tube.

A more carefully constructed artificial ear was used for tests recorded in this paper, but the design was altered only in mechanical details, and the performance was found to be practically the same as that of the experimental model.

The magnitude of the acoustical impedance depends thus on the volume of the cup and the cross-sectional area of the tube; these are 3 cm^3 and 0.3 cm^2 respectively. The extreme values of the equivalent volumes and areas determining the reactance and resistance components, respectively, of the real ears tested (including only those of normal hearing) are reproduced in Table 2, together with the values found from measurements on the artificial ear.

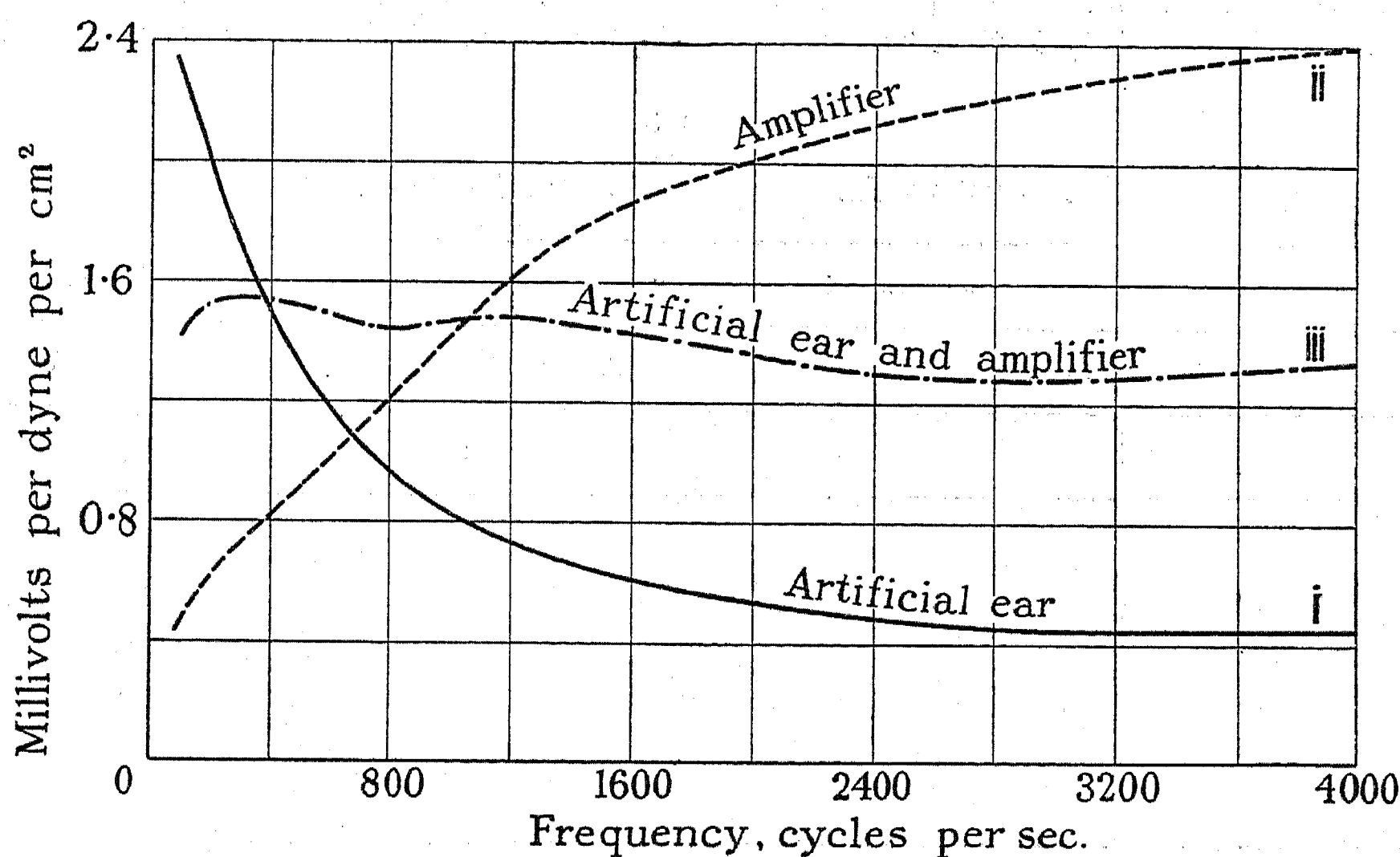


FIG. 2.

ensure a reasonably firm fit of the receiver on the ear, since trunk calls are generally more important conversations than local calls, and they are not liable to be received with excessive loudness.

The acoustical impedance, as viewed from the aperture of the ear-cap, is the ratio of pressure in the cavity formed between the cap and the ear to the rate of volume displacement of air in the aperture. It may simply be regarded as comprised of a reactance component, due to the elasticity of the air in the cavity, in parallel with a resistance component, due to work expended in vibrating the ear-drum and other exposed portions of the outer ear.

Based on measurements of these two components with real ears, an experimental artificial ear was constructed,‡ comprising essentially a small cup (to represent the reactance component) communicating with a length of

The frequency characteristic of the sensitivity of the artificial ear is shown by Curve (i) of Fig. 2, and that of the associated amplifier by Curve (ii). The overall frequency characteristic, Curve (iii), shows a sensitivity which is practically independent of the frequency.

It is of interest to compare the acoustical impedance of this artificial ear with that of the one designed by Inglis, Gray, and Jenkins,* who have published impedance characteristics and typical curves obtained from telephone receivers. Their frequency characteristic of a desk-stand receiver is very similar indeed to those obtained on the Bell-type receivers on the Post Office artificial ear.

In order to compare the acoustical impedances, the values shown in Table 2 have been converted to the equivalent acoustical resistance and reactance components in series, and the comparison is made in Table 3.

The "leak" is an aperture in the cup to represent the

* *Post Office Electrical Engineers' Journal*, 1929, vol. 21, p. 293.

† A. H. INGLIS, C. H. G. GRAY, and R. T. JENKINS: *Bell System Technical Journal*, 1932, vol. 11, p. 293.

‡ *Post Office Electrical Engineers' Journal*, 1930, vol. 22, p. 260.

* *Lcc. cit.*

leakage existing between the ear-cap and the air. The effect is to transform the cavity into a Helmholtz-type resonator and to introduce an acoustical resonance at a frequency which is low (say, below 500 cycles per sec.) when the leakage is small, i.e. when the receiver is firmly held to the ear.

If the receiver is moved, even slightly, from the firmly-held position, the frequency of the resonator is raised, and the frequency of resonance of the diaphragm will also be changed, the whole system comprising a double resonator. Further movement of the receiver away from the ear results in conditions more applicable to radiated sound than to sound pressures generated in a confined space. On the other hand, if the pressure with which the receiver is held to the ear is increased, the acoustical resonant frequency is made lower, but the acoustical impedance at higher frequencies remains substantially the same.

Consequently the firmly-held condition should be understood to apply to characteristics of receivers recorded in this paper. The probability is that the sound

those due to the reaction of the air on each side. It is of interest to know the orders of magnitude of these components and the factors affecting them, since the mechanical impedance of the diaphragm quite largely controls the performance of a receiver.

A mechanical impedance is defined as the ratio of force to velocity at the point or surface of application of the force. The velocity of the diaphragm is, of course, different at different parts of the surface, being zero at the edge and a maximum near the centre. It is therefore convenient to refer the mechanical impedance of the diaphragm to the velocity at the centre, and to imagine the diaphragm replaced by a piston (whose velocity is the same at all parts of the surface). The term "mechanical impedance of a diaphragm" should therefore be understood to mean the mechanical impedance of the equivalent piston—referred to the movement at the centre of the diaphragm. The amplitude of linear displacement of the equivalent piston is that of the centre of the diaphragm, and the area is such that the volume displacement of the piston is the same as that of the

TABLE 3.
Acoustical Impedances of Artificial Ears.

Frequency	Bell Laboratories artificial ear				P.O. artificial ear	
	Without leak		With typical leak		Without leak	
	Resistance	Reactance	Resistance	Reactance	Resistance	Reactance
Cycles per sec.	ohms	ohms	ohms	ohms	ohms	ohms
100	21	— 295	16	+ 15	—	—
300	14	— 112	56	+ 59	85	— 35
400	11	— 72	149	+ 5	80	— 50
800	15	— 45	15	— 45	45	— 60
1 200	11	— 24	11	— 24	25	— 50
2 300	5	— 15	5	— 15	10	— 25

pressures recorded on the artificial ear differ from those applied to a normal ear by not more than do the pressures applied to another normal ear—at least within the range of 300 to 3 000 cycles per sec.

In comparing the impedance values shown in Table 3 for the two artificial ears, it should be remembered that different ear-caps were used and that, since the Post Office ear-cap is less concave, smaller cavity volumes and therefore larger impedances are to be expected. This applies to both components of resistance and reactance.

It is of interest that the smallest range of variation of the impedances of real ears occurs at about 1 100 cycles per sec., which is also a usual frequency for the main resonance of a telephone receiver.

(4) METHODS USED FOR MEASURING THE MECHANICAL IMPEDANCE OF THE DIAPHRAGM OF A RECEIVER.

The mechanical impedance of a vibrating diaphragm has three components in series, namely that due to its own mechanical properties (mass, stiffness, etc.) and

diaphragm. Clearly this area depends on the form of displacement of the diaphragm.

Under the influence of uniformly applied pressures the form of displacement of the receiver diaphragm would very closely resemble that of an ideal clamped plate. Thus it can be calculated that the area of the equivalent piston would be one-third of that enclosed by the clamping edge of the diaphragm, and its mass one-fifth of the whole mass of this portion of the diaphragm.

Departures from the ideal form of displacement are to be expected, due to irregularities in the diaphragm and also to the fact that the applied forces are not uniformly distributed but concentrated over the poles of the magnet. Nevertheless the evidence to be recorded shows reasonable agreement with the plate theory when the ideal plate form of displacement is assumed for the diaphragm.

The method of clamping the diaphragm can also affect the mechanical impedance, and the screwed ear-cap can hardly be expected to provide a perfectly rigid clamping surface. Any alternative would, however, involve an unwanted modification of the receiver. The only

mechanical precaution taken was, therefore, the truing-up of the clamping surfaces of the ear-caps by machine.

Measurements of the impedances of diaphragms were made on a Bell-type receiver. For the most part the artificial ear was used, but some tests were also made with the receiver in the open in a room with non-reflecting surfaces, the sound pressures being measured by a condenser transmitter about 10 cm distant. In both cases the acoustical impedance in front of the diaphragm was known to a fair degree of accuracy. Measurements were made of the frequency of resonance, by means of a frequency bridge, and also of the decay factor; several repeat tests were made of the frequency of resonance after re-clamping the diaphragm, in order to obtain an average condition. The measurements were repeated with known alterations to the impedance behind the diaphragm, and sufficient data were thus obtained for evaluating the mechanical impedance of the diaphragm, in terms of its equivalent mass, stiffness, and resistance.

The alterations of the impedance behind the diaphragm were effected by changing the volume of air in the receiver cavity by introducing wax. It has been demonstrated by Mallett and Dutton* that if the reciprocal of this volume is plotted against the square of the corresponding frequency of resonance of the diaphragm, the points lie on a straight line. That this should be so requires the assumption that the resistance component of the impedance is not so large as to affect appreciably the frequency of resonance. With this assumption, which is generally reasonable, the slope and position of the straight line supply the data required to evaluate the mass m and stiffness factor s of the diaphragm.

When the artificial ear is used the relevant equation is:—

$$m\omega_0^2 = s + 8.3 \times 10^6 + \frac{48.2 \times 10^6}{Q''} \quad (1)$$

where ω_0 is 2π times the resonant frequency corresponding to the volume Q'' in the receiver cavity. The equation is derived in the Appendix.

When the receiver is tested in the open the impedance in front of the diaphragm is regarded as negligible and the equation reduces to:—

$$m\omega_0^2 = s + \frac{48.2 \times 10^6}{Q''} \quad (2)$$

The mechanical resistance R_M was obtained from the measurements of the decay factor Δ . These measurements were based on observations of sound pressures at five or six different frequencies in the neighbourhood of resonance with a constant current supplied to the receiver. Points for the pressure multiplied by the corresponding frequency were plotted against the frequency, and Mallett's circle construction† was used to evaluate the decay factor. The reason for multiplying the pressure by the frequency before applying the circle construction is that the resonance curve to which the construction is applicable is, for a mechanical system, that of velocity plotted against frequency for a constant applied force. The force was taken as proportional to the current supplied, but the velocity is proportional to the product of

pressure and frequency, since, over the small frequency range used, the acoustical impedance of the artificial ear is inversely proportional to the frequency.

With the artificial ear, the mechanical resistance of the diaphragm is given by:—

$$R_M = 2m\Delta - R'_M \quad (3)$$

where R'_M is that due to the artificial ear (see Appendix).

In the open it is taken as simply:—

$$R_M = 2m\Delta \quad (4)$$

The possibility of appreciable resistance behind the diaphragm was excluded, as far as possible, by the covering of hard wax of the filling. The assumption of zero resistance behind the diaphragm may be invalidated when the cavity is so small as to involve constriction, or when the exposed surface area is large. Consequently the resistance measurements were made for moderate-size cavities only.

(5) THE MECHANICAL CONSTANTS OF CERTAIN DIAPHRAGMS.

Diaphragms made from three different kinds of steel have been tested; the types will be designated A, B, and C, respectively. Type A is stalloy—the standard material for diaphragms of the Post Office receivers at the present time. Types B and C refer to sample diaphragms of different steels supplied by two manufacturers; they serve to illustrate variations of the performance of receivers which are liable to occur owing to the use of different diaphragm materials.

All the diaphragms were finished with a coating of the usual black varnish. Thicknesses were measured over varnish, and the average of a number of thicknesses at different parts of the surface will be quoted—in thousandths of an inch (mils)—as a suffix to the type letter to designate the particular sample diaphragm. Thus A (10.2) refers to a stalloy diaphragm of average thickness 0.0102 in., over varnish.

The first test was made with diaphragm A (10.2) in the receiver as obtained from stock. The frequency at resonance was $f_0 = 1100$ cycles per sec. and the decay factor was $\Delta = 500$, on the artificial ear. The receiver was then filled with wax, smoothed off to the level of the clamping surfaces. Known cavity volumes were formed by cutting the wax away and weighing the amount removed. Finally the wax was melted out by gentle heating, and it was found that the decay factor was reduced to $\Delta = 390$. Clearly the impregnation of the coils had removed a considerable resistance from the mechanical impedance due to the receiver cavity.

Five series of tests were carried out, the particulars of which are detailed in Table 4. The series are arranged in such order that the first three compare different diaphragms under identical conditions, while the last three compare the results of measurements on the same diaphragm under different conditions of test.

The last three columns show the equivalent mass, stiffness, and resistance, calculated from the data given in the preceding columns by the methods described in Section (4). Assuming the plate theory of vibration,

* *Loc. cit.*, Fig. 9.

† *Journal I.E.E.*, 1924, vol. 62, p. 517.

and also that the whole mass of a diaphragm is uniformly distributed, we can calculate the equivalent mass as one-fifth of the whole mass of the portion enclosed by the clamping surface. On this basis the equivalent mass of B (10·1) would be 0·52 gramme, of C (10·5) 0·6 gramme, and of A (10·2) 0·56 gramme—on the whole a rather surprisingly close agreement with the measured values shown in the Table.

Comparison between the first three series calls for little comment; obviously the properties of steel B are similar to those of A, so far as this test is concerned, while steel C has appreciably greater equivalent mass and stiffness. Since the resistances are of similar magnitude, the greater mass causes a smaller decay factor. Re-

diaphragm was about 30 times that of the amplitude for series 3—at the resonant frequency in each case. Presumably, therefore, the mechanical constants of the diaphragm are, within wide limits, substantially independent of the amplitude of vibration.

The apparent increase in the mechanical resistance (R_M) of series 4 by comparison with series 3 is quite probably not real. By ignoring the resistance due to radiation in the free-air test, we have included it with that of the diaphragm, and its magnitude may be estimated to be of the order of 20.

It had long been recognized that a considerable portion of the mechanical resistance of the diaphragm of a receiver was due to the presence of the magnetic flux,

TABLE 4.
Measurements of Mechanical Constants of Three Diaphragms.

Test series	Measured				Calculated		
	f_0	$\omega_0^2 \times 10^{-6}$	$1/Q''$	Δ	m	s	R_M
(1) Diaphragm B (10·1).—Receiver and ear-cap normal. Artificial ear ..	1 510	90	0·488	—	0·53	$16·5 \times 10^6$	120 100
	1 360	73	0·266	308			
	1 247	61	0·167	317			
	1 200	55	0·069	—			
(2) Diaphragm C (10·5), otherwise as in (1)	1 515	91	0·488	—	0·63	26×10^6	120 110
	1 390	76	0·266	257			
	1 295	66	0·167	263			
(3) Diaphragm A (10·2), otherwise as in (1)	1 430	81	0·368	—	0·53	17×10^6	105 100
	1 330	70	0·244	300			
	1 260	63	0·167	315			
(4) A (10·2).—Diaphragm exposed. Free air	1 282	65	0·368	—	0·535	17×10^6	140 130
	1 170	54	0·244	130			
	1 090	47	0·167	121			
(5) A (10·2).—Receiver demagnetized. Normal ear-cap. Artificial ear ..	1 430	81	0·404	—	0·56	$17·5 \times 10^6$	40 45
	1 330	70	0·253	222			
	1 230	60	0·160	260			
	1 180	55	0·069	—			

sonance occurs at similar frequencies for all three diaphragms, when, of course, similar cavity volumes (Q'') are considered.

The same diaphragm was used for each of the test series 3, 4, and 5, so that differences in the results—where they are discernible by the experimental methods applied—may be attributed to external influences on the diaphragm.

In spite of the large difference in the external acoustical load due to the artificial ear, as compared with free air, the masses and stiffness measured in series 3 and 4 are in close agreement, a fact which provides confirmation of the validity of the method. A larger current was used for series 4, and since also the applied mechanical resistance was much smaller (it has been considered negligibly small), the amplitude of displacement of the

and test series 5 was carried out with the steady flux eliminated. Some oscillographic records had been taken of the decay of sound pressures from a telephone receiver when current, at the frequency of resonance, was suddenly switched off. The decay factors measured from the oscillograms were less than those obtained from the frequency characteristics. For example, for a certain receiver in free air, Δ was about 110 from the oscillogram and 190 from the frequency characteristic. A difference between the two conditions of test is that eddy currents in the diaphragm due to the alternating flux are absent in the one and present in the other. The eddy currents link with the direct flux, the magnitude of which is continually varying due to the movement of the diaphragm. There is the further consideration, common to both tests, that the movement of the diaphragm, an

electric conductor, is subject to a braking force in the magnetic field.

In order to demagnetize the receiver for the tests of series 5, the permanent magnet was replaced by a soft-iron bar, and demagnetizing current was passed through the coils with the diaphragm clamped in position. The frequency of the applied force was thus twice that of the current supplied to the coils, hence resonance occurred when the frequency of the current was one-half of the frequency of resonance of the diaphragm; even so there remained a substantial peak also at the frequency of resonance. Measurements of f_0 and Δ at both the frequencies were in good agreement.

From Table 4 it is seen that a somewhat larger equivalent mass was obtained with the demagnetized receiver. That the removal of the flux should affect the mechanical reactance as well as the resistance is possible, but it cannot be positively stated that the observed increase of mass is greater than the accuracy of measurement.

The decay factor and mechanical resistance are definitely less in series 5 than in series 3. The value of R_M is calculated from that of m obtained in the same series, and if m were taken as 0.53 instead of 0.56 in series 5, R_M would be reduced to rather less than 30. The resistance R_M is obtained as a difference between two quantities of comparable order of magnitude, and the accuracy is therefore rather uncertain when the difference is quite small.

(6) METHODS USED FOR MEASURING FLUX, PULL, AND AIR-GAP.

The mechanical impedance of the diaphragm having been measured, it is now of interest to study the magnetic forces by which the diaphragm is actuated. For this purpose measurements were made of the magnetic flux leaving the pole-faces. Small search coils were wound with 40 or 50 turns each of fine enamelled wire, fitting round the pole-tips. It was found that the flux here was considerably less than the whole flux carried by the diaphragm—as measured by a search coil round the diaphragm between the poles.

The search coils were used for observing both the direct and the alternating components of the flux entering the air-gap; for the former the usual ballistic-galvanometer method was employed. When the effects of different air-gaps were to be studied, a receiver was re-assembled with the case inverted in order to free the pole-pieces from obstruction, and the length of the gap was controlled by cementing small splinters of microscope cover glass of the required thickness, two on each pole-face.

For measurements of the direct flux in a receiver as ordinarily assembled, the search coils were placed in position, but, before the diaphragm was clamped on, a direct current through the receiver coils was adjusted until no throw was read on the galvanometer when the diaphragm was suddenly removed. The diaphragm was then clamped by the ear-cap, and the flux was measured by switching this current on and off. The demagnetizing effect of the current on the permanent magnet was not serious; in fact, at the conclusion of the tests on the handset-type receiver, the magnet strength was found to be still up to the average for the type.

The arrangement with the receiver case inverted was

also used for measuring the steady force, or "pull," exerted between the poles and the diaphragm. The diaphragm was supported on a ring suspended from a spring balance and held on the glass spacing-pieces by the magnetic force. The tension in the balance was increased very gradually until the diaphragm was pulled off. The method is rather crude, and slight variations from a balanced and central pull register comparatively small tensions. However, each recorded measurement is the result of a large number of individual tests and represents the maximum force which could be obtained and repeated, but not exceeded.

The actual air-gap of a receiver, as normally assembled, was measured by means of a micrometer depth-gauge. First the pole-faces were cleaned and the depth below the clamping surface measured at a number of points. Receivers for test were chosen with small differences only, i.e. with pole-faces parallel with the clamping surface. Next the diaphragm was clamped on by an ear-cap with an enlarged aperture and a flat face. A strip of metal foil was held to the diaphragm by a light smear of vaseline to form a metallic surface on the centre of the diaphragm; it was used to indicate, by electrical conduction, a contact between the depth-gauge and the diaphragm. The compensating direct current was passed through the receiver coils to neutralize the flux at the pole-pieces, and the depth from the face of the ear-cap to the diaphragm was noted; the current was then switched off and the increase in depth, or displacement due to the flux, was measured.

(7) FLUX AND PULL OF TYPICAL BELL RECEIVERS.

The results of measurements with different air-gaps are shown in Table 5, for diaphragms of three different kinds of steel.

TABLE 5.

Flux and Pull of Typical Bell Receiver.

Diaphragm	Air-gap	Pull (F)	Flux (Φ)	Effective pole area	Ratio of effective to actual area
	mils	grammes	lines	cm ²	
A (10.2)	4.5	180	955	0.205	0.51
B (9.3)	4.5	175	900	0.19	0.48
C (11.5)	4.5	180	920	0.19	0.48
A (10.2)	9.5	95	730	0.23	0.58
B (9.3)	9.5	90	720	0.235	0.59
C (11.5)	9.5	85	700	0.235	0.59
A (10.2)	10.5	85	700	0.235	0.59
B (9.3)	10.5	85	695	0.23	0.58
C (11.5)	10.5	80	675	0.23	0.58
A (10.2)	15	56	585	0.25	0.63
B (9.3)	15	55	580	0.25	0.63
C (11.5)	15	53	565	0.245	0.61

In the fifth column the effective area of the poles is calculated from the theoretical formula for a uniformly distributed flux, the relevant equation being:—

Effective area = $\frac{\Phi^2}{981 \times 8\pi F}$ cm² . . . (5)

The actual area of the two pole-faces was about 0.4 cm².

The relation between pull and flux is obviously influenced by the geometrical distribution of the lines of force in the air-gap. There is also the further consideration that a few of the lines are not carried by the diaphragm. A test was made with the search coils over the pole-tips, but on the other side of the diaphragm, in order to observe the order of magnitude of the flux leaking through the diaphragm. The results for three thicknesses of stalloy diaphragm are given in Table 6.

TABLE 6.

Diaphragm	Flux entering air-gap	Flux leaving diaphragm on far side
A (10.2)	800	4
A (8.3)	740	18
A (6.5)	635	36

The flux entering the air-gap was also measured with the receiver, ear-cap, and diaphragms, used for the experiments described in Section (5). A current of about 180 mA in the receiver coils was required to neutralize the effect of the permanent magnet, and the flux was measured by switching off this current. A few repeat tests with different clampings gave the following results:—

- Diaphragm A (10.2):—745, 770, 755, 755, lines.
- „ B (10.1):—770, 780, 755, lines.
- „ C (10.5):—680, 690, 670, lines.

(8) FLUX, PULL, AND AIR-GAP, OF TYPICAL HANDSET RECEIVERS.

Measurements corresponding to those recorded in Table 5 were made on a handset receiver, and the results are shown in Table 7. On this occasion stalloy diaphragms of different thicknesses were used, instead of diaphragms of different materials.

The actual area of the two pole-faces was about 0.3 cm².

A comparison of Tables 5 and 7 for diaphragm A (10.2) reveals a slightly greater flux for the Bell receiver than for the handset receiver, but a definitely smaller pull. It may be argued that the pull depends on the amount of flux entering the air-gap and on the geometrical distribution, which in turn depends on the reluctances of the diaphragm and air-gap, on the shape and size of the pole-pieces, and on the magnet strength. The last columns of Tables 5 and 7 give an indication of the consequences of altered distributions of flux in the air-gap, resulting from considerable changes in the reluctances of the air-gap and of the diaphragm.

Flux and air-gap measurements made on a handset receiver, as ordinarily assembled, are recorded in Table 8. A current of 155 mA was required in the coils to neutralize

the flux at the pole-tips. The depth of the pole-faces was 0.014 in. below the clamping surface.

Some experiments were also made to obtain the relation between flux entering the air-gap and m.m.f. due to direct current in the coils of this receiver. The total number of turns in the coils is not known exactly; it was approximately 2 000. Readings were taken of the flux for dif-

TABLE 7.

Flux and Pull of Typical Handset Receiver.

Diaphragm	Air-gap	Pull (F)	Flux (Φ)	Effective pole area	Ratio of effective to actual area
	mils	grammes	lines	cm ²	
A (19)	4.5	>230	1 020	—	—
A (10.2)	4.5	210	880	0.15	0.50
A (8.3)	4.5	155	780	0.16	0.53
A (6.5)	4.5	110	650	0.155	0.52
A (19)	10.5	120	710	0.17	0.57
A (10.2)	10.5	110	690*	0.175	0.58
A (8.3)	10.5	100	650	0.17	0.57
A (6.5)	10.5	80	580	0.17	0.57
A (19)	15	80	590	0.18	0.60
A (10.2)	15	75	580	0.18	0.60
A (8.3)	15	70	570	0.19	0.63
A (6.5)	15	60	525	0.185	0.62

* The total flux through the diaphragm was measured for this condition and found to be 1 140 lines.

ferent values of current in the coils when assisting the permanent flux, when opposing it, and when reversed. Diaphragm A (10.2) was used, both as normally clamped and also with a fixed air-gap of 0.0105 in. The results of the tests are shown in Table 9.

The initial readings when the current is first switched on and then off may differ slightly according to the

TABLE 8.

Flux and Air-gap of a Handset Receiver.

Diaphragm	Flux	Displacement due to flux	Air-gap
	lines	mils	mils
A (19)	790	—	—
A (10.2)	800	3.3	10.7
A (8.3)	770	4.5	9.5
A (6.5)	685	6.0	8.0

initial state of the magnetic circuit; after this the readings were found to be similar and closely repeatable. The figures in Table 9 therefore refer to the change of the flux entering the air-gap due to a sudden change of current in the receiver coils—after the magnetic circuit has accommodated itself to this change. It will be seen that the change of flux due to reversal of the current is slightly greater than the sum of the changes obtained by

applying the current first in one direction and then in the other.

In plotting Fig. 3 from the data shown in Table 9, the measurements for the reversal of current have been ignored. The value of the flux with no current in the coils is taken as that due to the opposing current of 155 mA, since this was the current required to neutralize the permanent flux exactly. The curves in Fig. 3 therefore indicate the flux entering the air-gap for different values of direct current in the receiver coils, after the magnetic circuit has been stabilized by first switching the current on and off. The difference in the shape of the

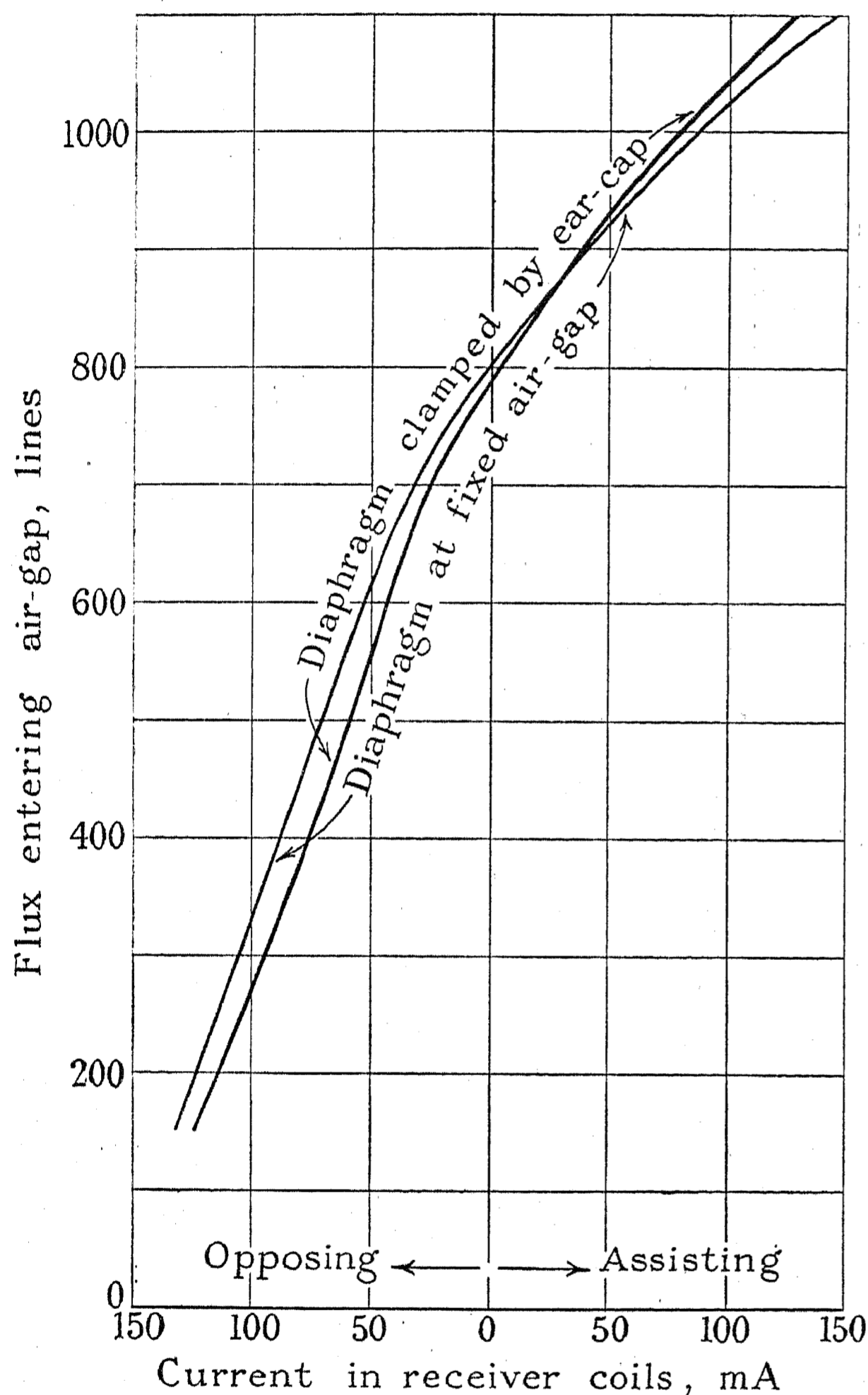


FIG. 3.—Flux/current curves for a handset receiver.

two curves is caused by changes in the air-gap, liable to occur when the diaphragm is clamped by an ear-cap but prevented when the air-gap is fixed.

It is seen that if the flux is increased above the normal value of 800 the slope of the curve tends to decrease, and vice versa. Now the slope is, to some extent, a measure of the rate of change of flux per unit rate of change of current, i.e. of the alternating flux per unit of alternating current. That the slope of the curve is no complete measure of the alternating flux is evident, since the reluctance of the magnetic circuit will vary with the

frequency. Moreover, as mentioned above, the curves apply only to variations of flux and current from the condition of zero current, and the slope may not be the same for variations of current about some other point on the curve.

At the same time there is evidence to support the reasonable supposition that a larger steady flux generally involves a smaller alternating flux per unit current, if

TABLE 9.

Change of Flux entering Air-gap due to Direct Current in Coils.

Current mA	Diaphragm clamped by ear-cap			Fixed air-gap of 0.0105 in.		
	Assisting	Opposing	Reversal	Assisting	Opposing	Reversal
10	28	29	58	25	25	50
20	57	67	127	48	57	106
40	114	170	292	97	130	230
60	164	292	464	141	235	385
80	211	404	628	185	355	555
100	256	519	787	224	475	705
125	300	640	960	270	610	905
155	360	790	1 152	308	800	1 120

only on account of the degree of magnetic saturation of the diaphragm. Since the alternating force on the diaphragm depends on the product of the steady flux and the alternating flux, it is clear that the sensitivity of a receiver is not raised in direct proportion to an increase of the steady flux. The matter was further investigated by the tests recorded in the next Section.

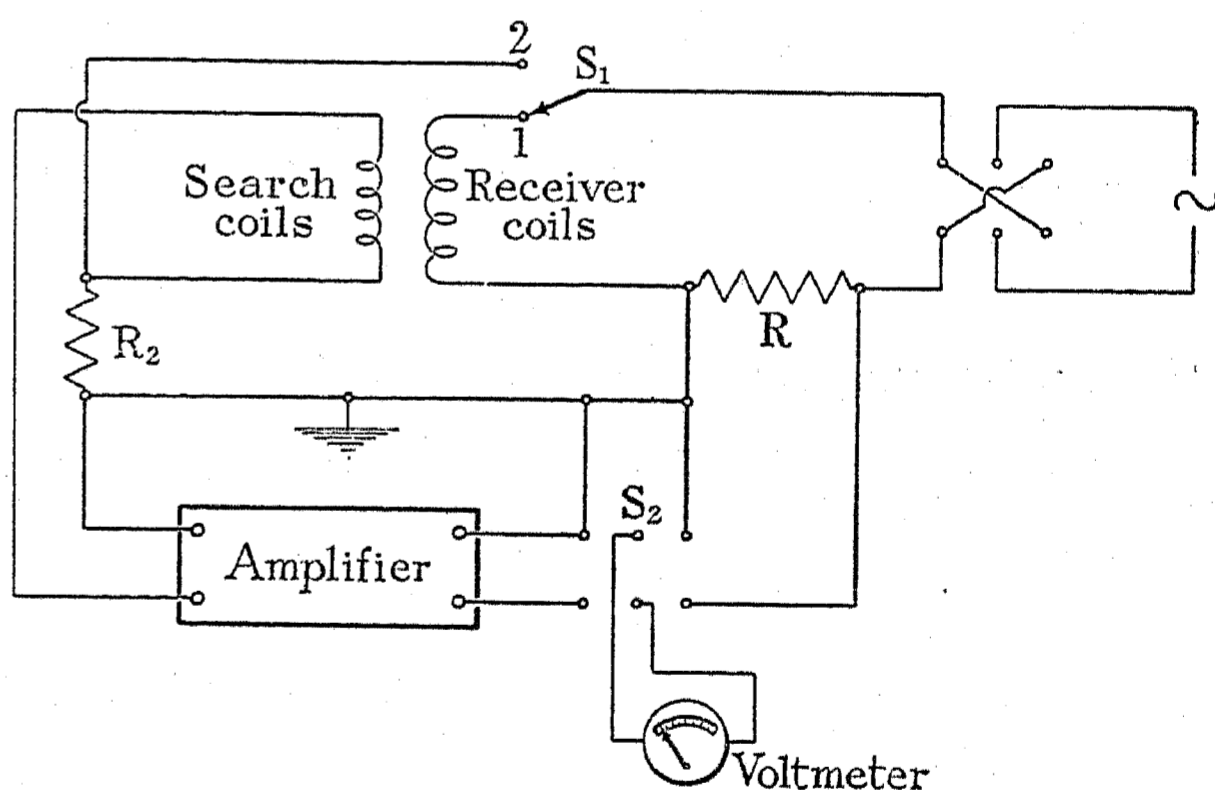


FIG. 4.

(9) MEASUREMENTS OF ALTERNATING FLUX.

The e.m.f. generated in the search coils due to alternating current in the receiver coils was measured on the circuit sketched in Fig. 4, the procedure being as follows: With the switch S_1 in position 1, and with a suitable setting for the gain of the amplifier, the resistance R was adjusted to such a value, say R_1 , that the reading of the voltmeter was the same for both positions of the switch S_2 . Next, with switch S_1 in position 2 and with a suitable setting of the small resistance R_2 , the

resistance R was again adjusted to a value, say R_0 , which gave equal readings for both positions of switch S_2 . With these readings the e.m.f. in the search coils, E volts per mA of current in the receiver coils, is obtained from

$$E = \frac{R_1 R_2}{1\,000 R_0} \dots \dots \dots (6)$$

Since the voltmeter was of the valve-operated type, reading peak values rather than r.m.s. values of the

the receiver coils; it was also observed that the flux per unit current increased by about 4 per cent when the current was doubled, and decreased by about the same amount when the current was halved—presumably as a consequence of magnetic hysteresis. Concurrently with the taking of certain frequency-characteristic records—to be described later—some measurements were made of the alternating flux entering the air-gap when diaphragm A (10·2) was clamped at different spacing distances on the handset-type receiver.

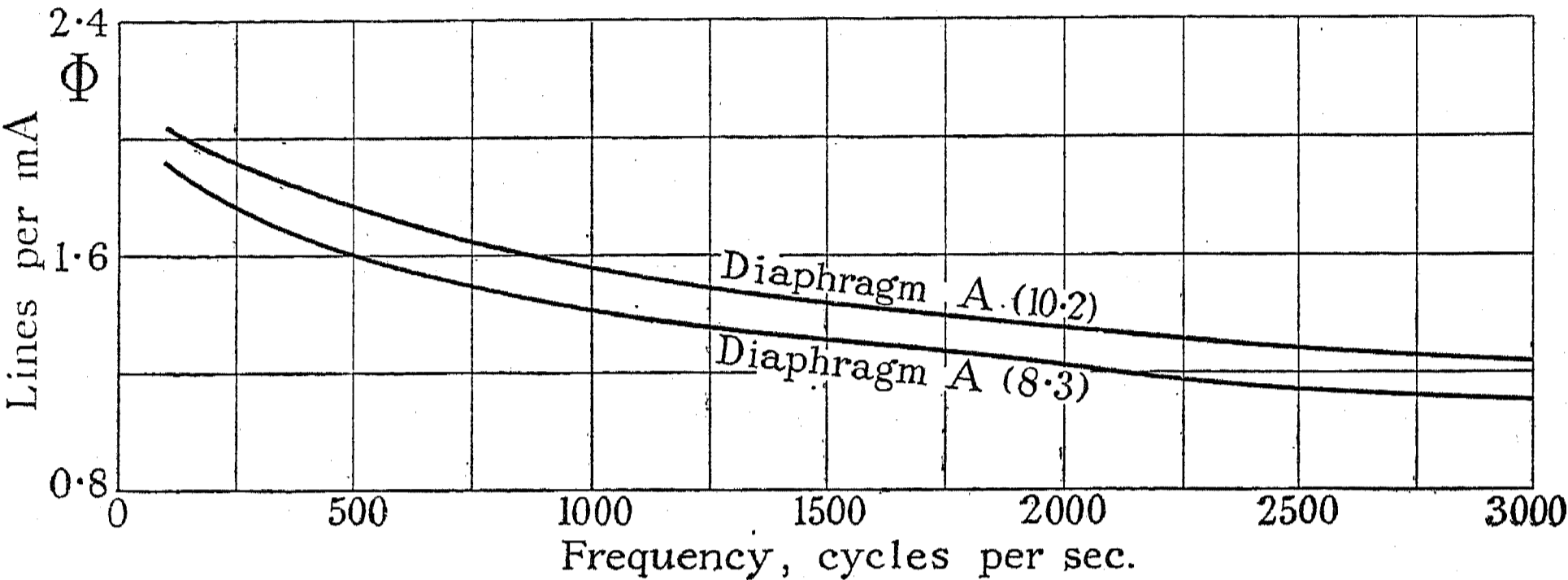


FIG. 5.—Alternating flux per unit current for diaphragm held at 0·0105-in. gap.

applied p.d., the reversing key was inserted in the supply circuit from the oscillator. It was used to check the purity of the wave-form by observing that the reading of the voltmeter was the same when the wave was reversed.

If the alternating flux through the search coils has the form $\hat{\Phi} \sin \omega t$, the instantaneous value of the induced e.m.f., in volts, is

$$e = \frac{N}{10^8} \hat{\Phi} \omega \cos \omega t \dots \dots \dots (7)$$

where N is the number of turns on the search coils.

TABLE 10.

Relation between Air-gap and Depth of Pole-faces on Handset Receiver.

Depth of pole-faces	Displacement due to flux	Air-gap
mils	mils	mils
9	5	4
14	3·5	10·5
19	2·5	16·5

Hence the r.m.s. value of the alternating flux through the pole-tips, per mA of current, is

$$\Phi = \frac{10^8 E}{N \omega} \dots \dots \dots (8)$$

With a fixed air-gap of about 0·0105 in., flux measurements were made at different frequencies, and the results are plotted in Fig. 5 for diaphragms A (10·2) and A (8·3). The measurements were made with a current of 1 mA in

For this purpose the receiver case was cut away at the clamping surface by 0·005 in., thus reducing the depth of the pole-faces from 0·014 to 0·009 in. Two brass spacing rings were cut, thicknesses 0·005 and 0·01 in. respectively, so that the depth of the pole-faces could be changed from 0·009 to 0·014 or to 0·019 in. Air-gap measurements with the diaphragm clamped by an ear-cap gave the results shown in Table 10.

The alternating flux, for 1 mA of current in the receiver coils, was measured at one or two frequencies remote from that of resonance of the diaphragm, as recorded in Table 11.

TABLE 11.
Variation of Alternating Flux with Air-gap.

Depth of pole-faces	9 mils	14 mils	19 mils
Frequency	Flux per mA		
cycles per sec.	lines	lines	lines
200	1·7	2·2	2·4
400	1·6	1·97	2·2
2 000	—	1·34	1·52
3 000	1·06	1·26	1·4

Clearly the reduced reluctance, for alternating flux, due to a smaller air-gap is more than compensated by the increased reluctance due to the greater density of steady flux in the diaphragm.

(10) METHOD OF RECORDING FREQUENCY CHARACTERISTICS.

The frequency characteristics of sound pressures generated by the receiver on the artificial ear were

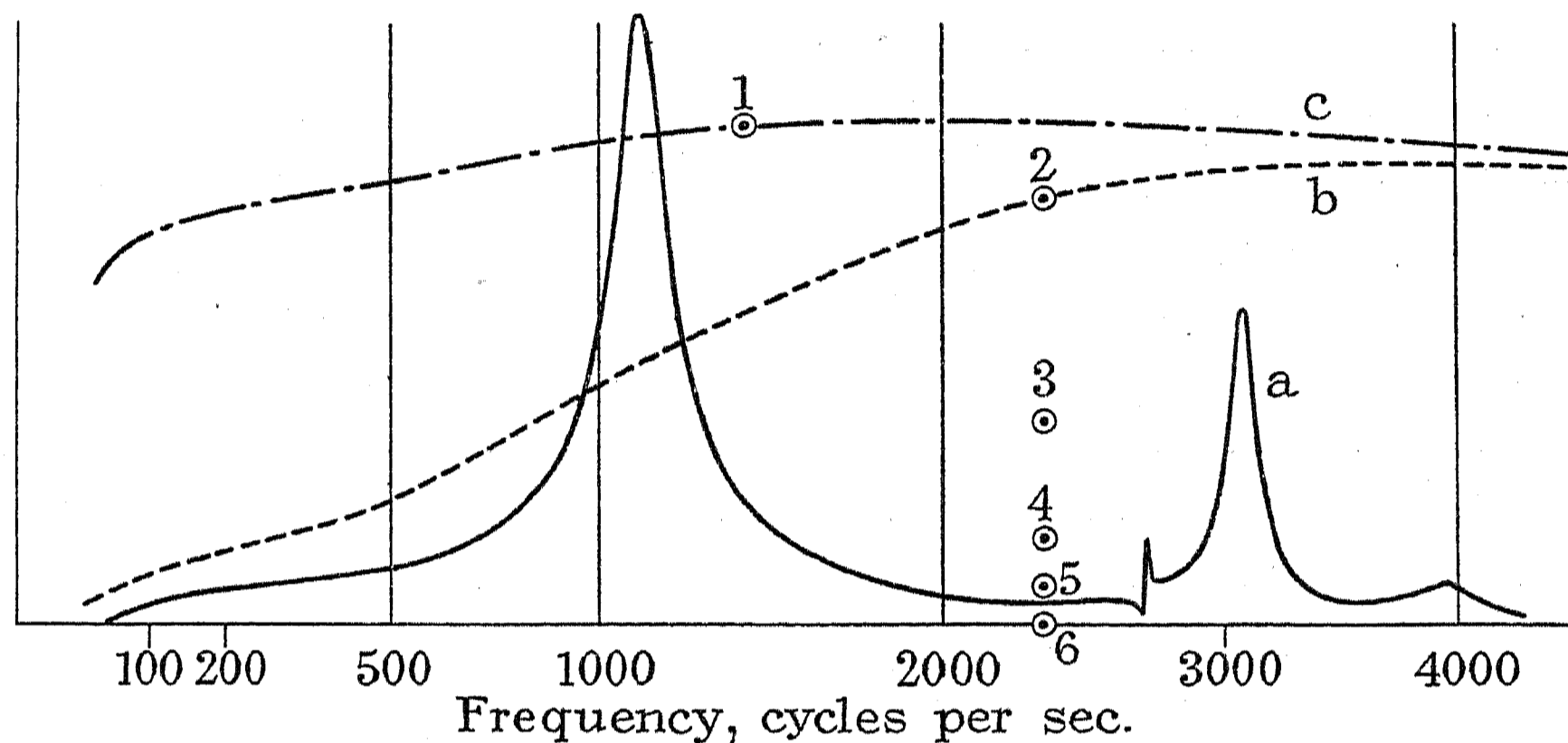
recorded by supplying the receiver with constant current from a heterodyne oscillator. The amplified output from the artificial ear was connected to a rectifier, with a nearly straight-line law, to deflect the spot of light from a reflecting galvanometer on to a drum rotating on the shaft of the variable condenser which controlled the frequency of the oscillator. Instead of a photographic record, a pencil tracing was made by hand, the pencil being carried on an arm to slide across the paper, tracing the path of the spot of light.

The current supplied to the receiver, and the combined sensitivity of the artificial ear and its amplifier, were both nearly independent of frequency, and the amplitude

sound pressures generated on the artificial ear. In drawing the frequency characteristics shown in Figs. 7 to 13 all the corrections were applied, and the sensitivity of the receiver, in dynes per cm² per mA, was evaluated from the tracings by means of the equation

$$\text{Sensitivity} = \frac{R_0 a}{z b} \quad (9)$$

where a and b are the ordinates of curves (a) and (b) respectively, after correction from the amplitude/response curve of the rectifier, and z is the sensitivity of the artificial ear in millivolts per dyne per cm² (curve i of Fig. 2).



Point 1; 0.26 mA.
Point 2; $R_0 = 80$ ohms.
Point 3; $R_0 = 40$ ohms.
Point 4; $R_0 = 20$ ohms.
Point 5; $R_0 = 10$ ohms.
Point 6; $R_0 = \text{zero}$.

FIG. 6.

response of the rectifier was nearly linear. However, with each frequency characteristic taken, sufficient data were also recorded to enable variations to be taken into account and to scale the curve in terms of dynes per cm² per mA.

In Fig. 6 is reproduced a typical example of the records obtained from the drum. (This is the record from which the full-line curve of Fig. 7 was drawn.) Current from the oscillator is fed through a comparatively large resistance to the receiver under test, in order to maintain a substantially constant current in the receiver, and the output from the artificial ear is traced [curve (a)]. A record of the current is obtained [curve (c)] by switching the rectifier across the resistance in series with the receiver, and a note is made of the p.d. at a convenient frequency (point 1).

Next the current is switched through an equal impedance (including that of a receiver similar to the one under test but not on the artificial ear) and through a small resistance R_0 in series with the condenser transmitter in the artificial ear, and the output from the amplifier [curve (b)] is traced. The calibration of the rectifier is checked at a single frequency by marking the positions of the spot of light for different values of R_0 (points 2 to 6). Finally the zero lines of frequency and amplitude are traced and the frequency calibration is checked by marking certain frequencies from settings on a frequency bridge.

This procedure provides a complete record, though actually the overall response is so nearly linear that the ordinates of curve (a) are nearly proportional to the

(11) FREQUENCY CHARACTERISTICS.

The effects of certain modifications to a receiver on the sensitivity at different frequencies are illustrated by the characteristics shown in Figs. 7 to 11 for a single handset-type receiver. All the curves were taken with a current

TABLE 12.

Frequency Characteristics of a Handset-Type Receiver.

Fig. No.	Curve	Diaphragm	Cavity behind diaphragm	Spacing distance	
				Of cap	Of pole-faces
7	Full	B (9.3)	Normal (25 cm ³)	mils 45	mils 14
	Broken	C (11.5)	Ditto	45	14
8	Full	A (10.2)	Ditto	45	14
	Broken	A (8.5)	Ditto	45	14
9	Full	A (10.2)	Ditto	20	14
	Broken	A (10.2)	Ditto	10	14
10	Full	A (10.2)	0.7 cm ³	45	14
	Broken	A (10.2)	0.7 cm ³	10	14
11	Full	A (10.2)	Normal	45	19
	Broken	A (10.2)	Ditto	45	9

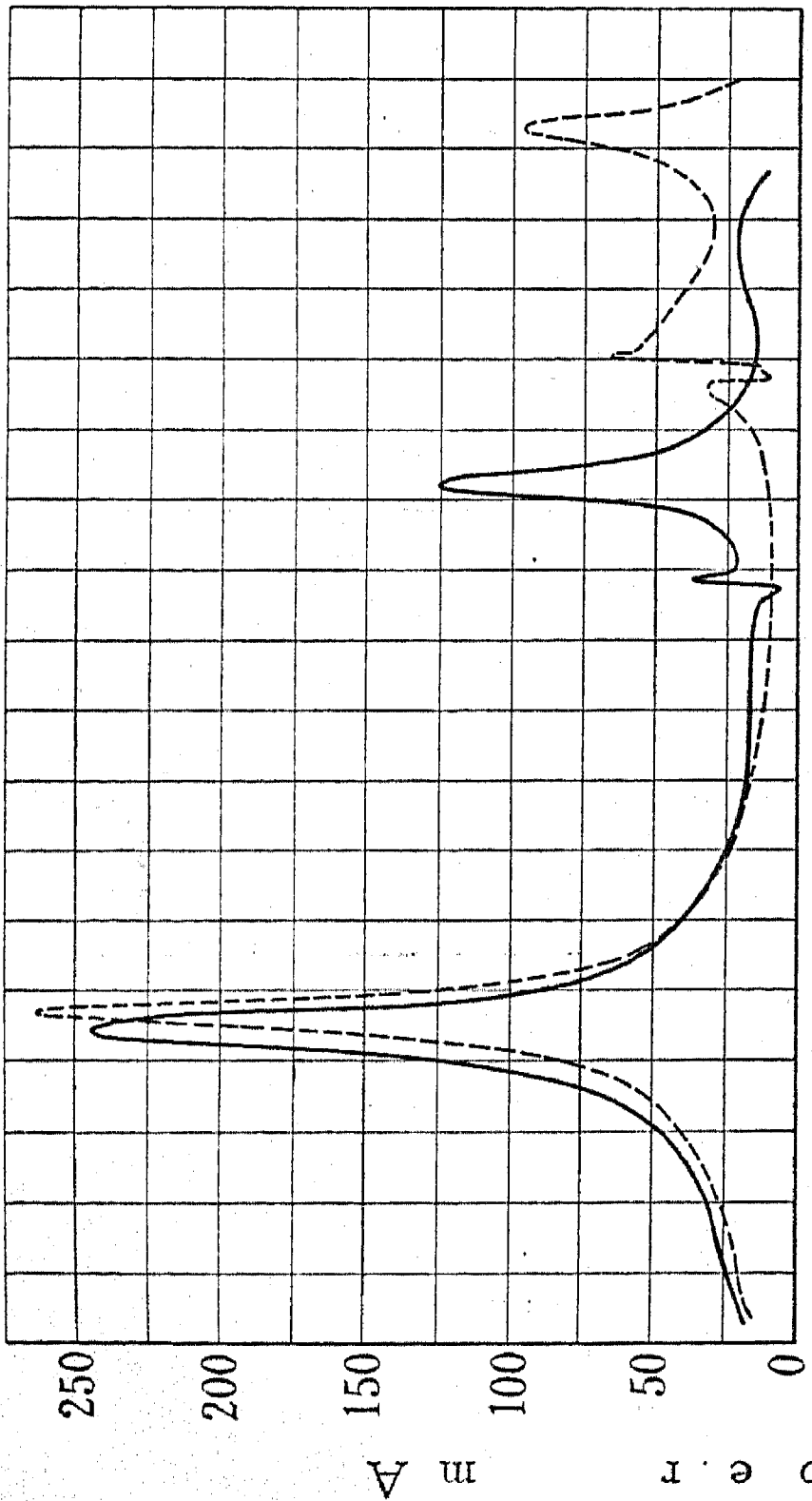


FIG. 7.

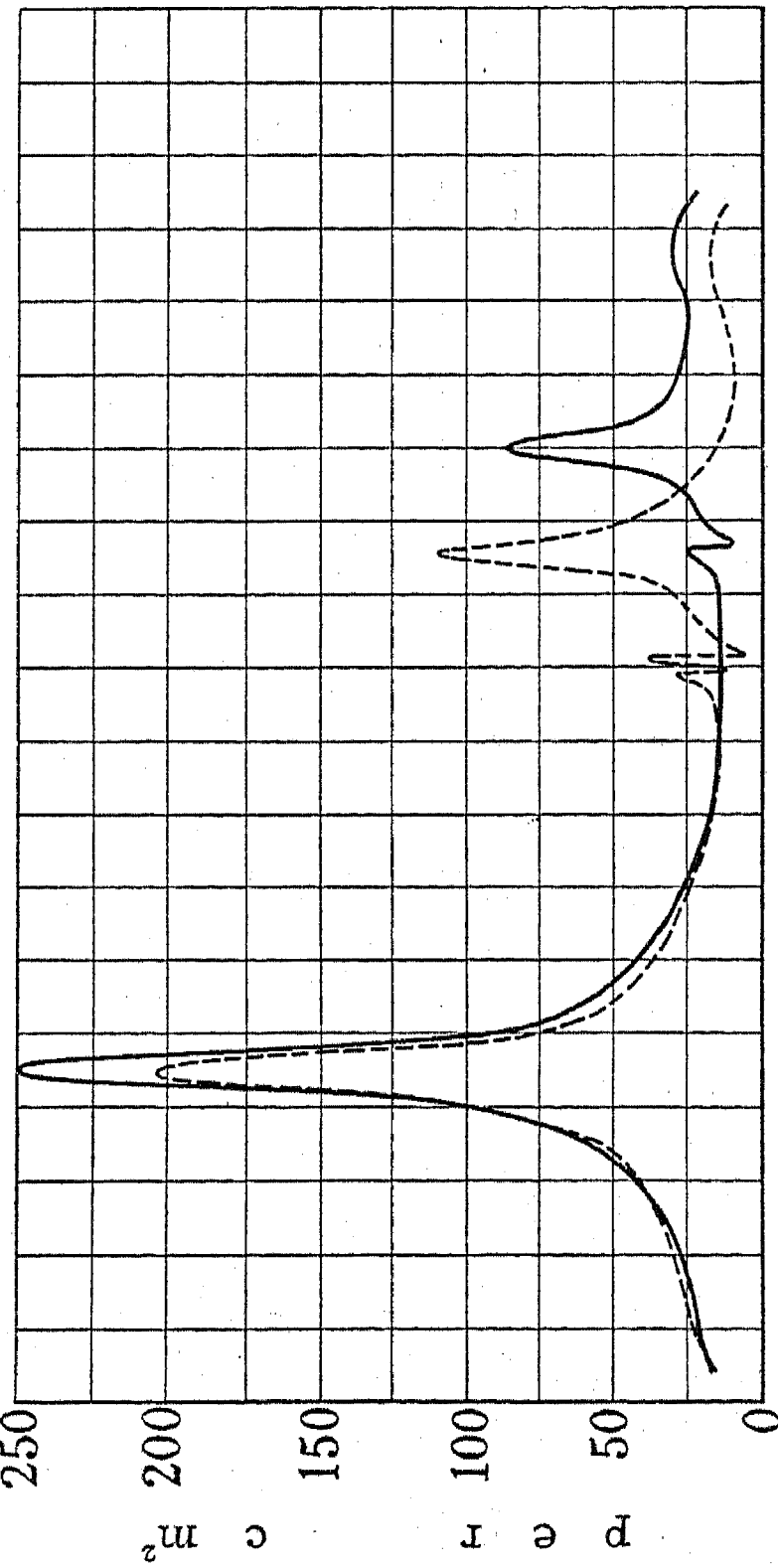


FIG. 8.

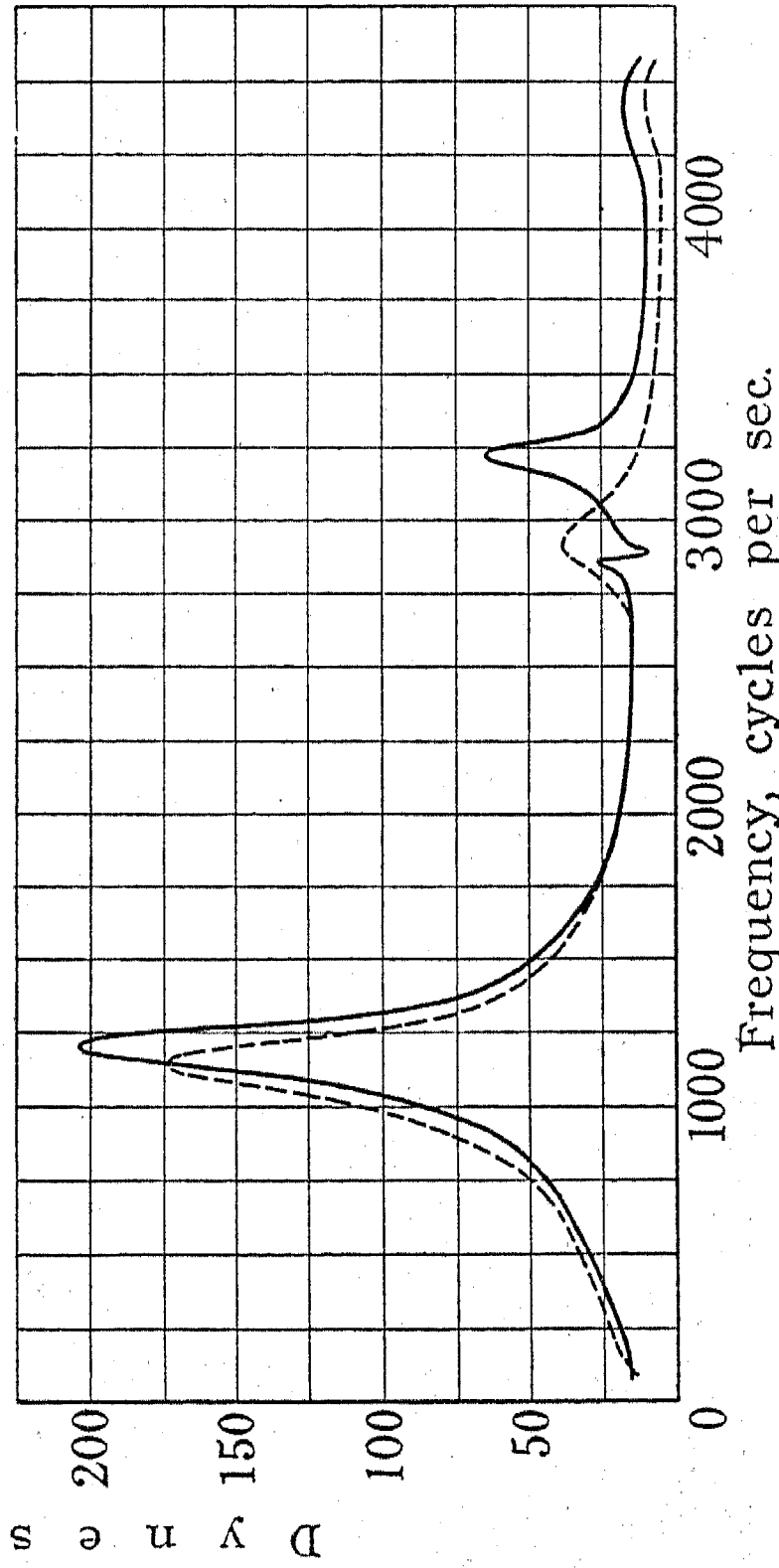


FIG. 9.

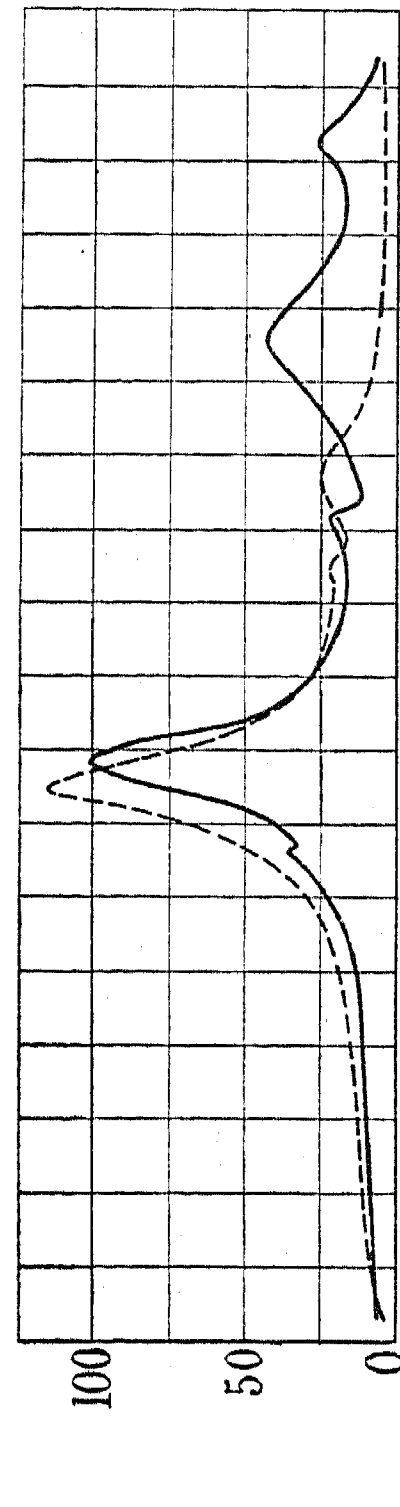


FIG. 10.

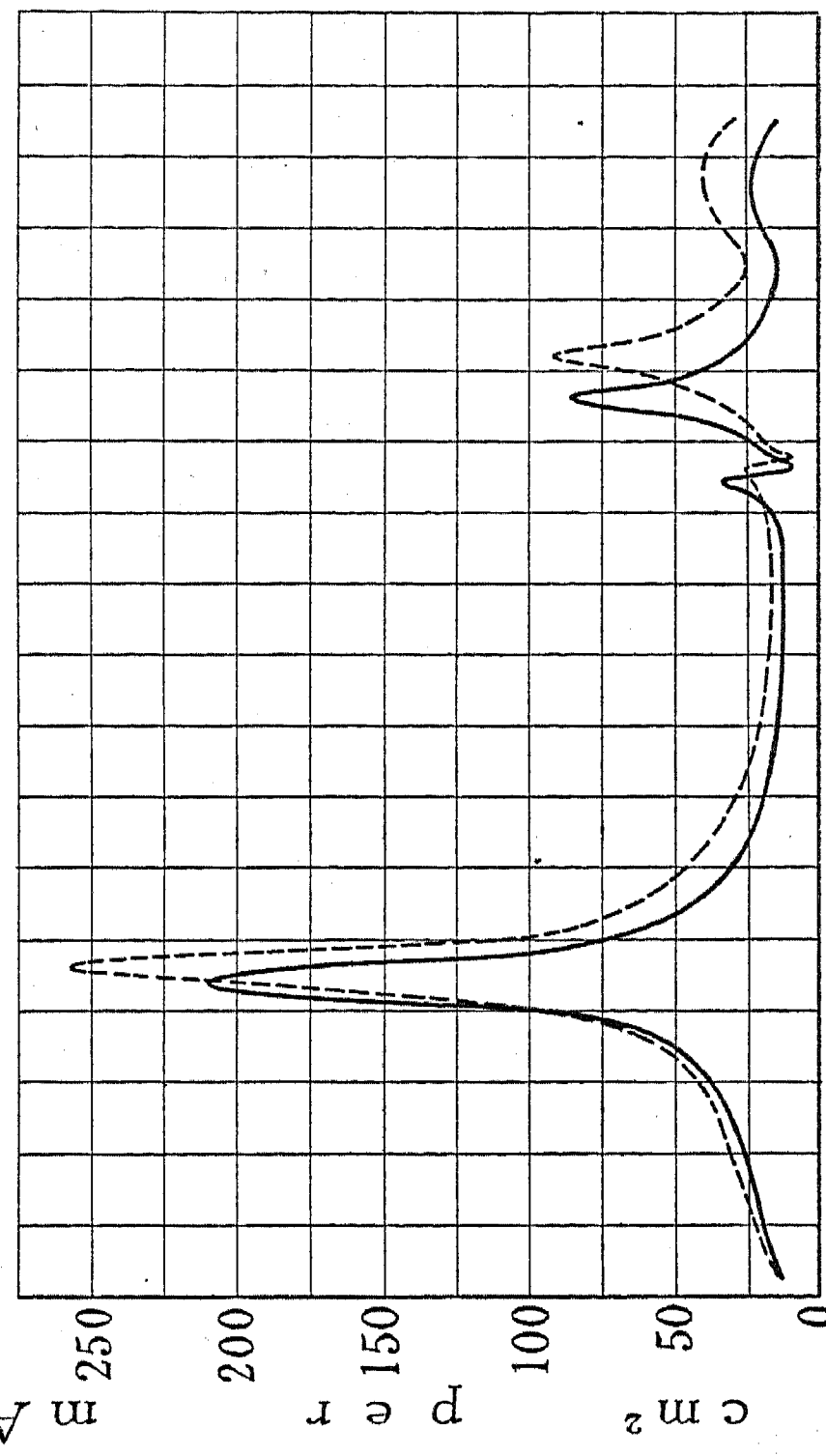


FIG. 11.

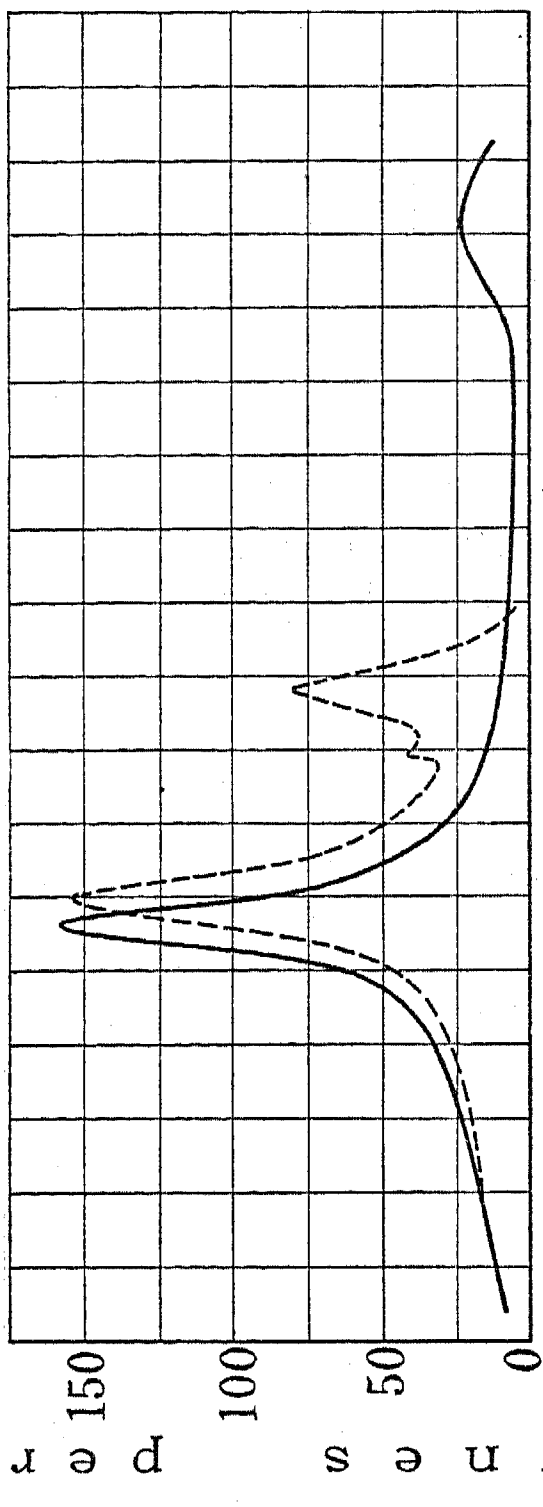


FIG. 12.

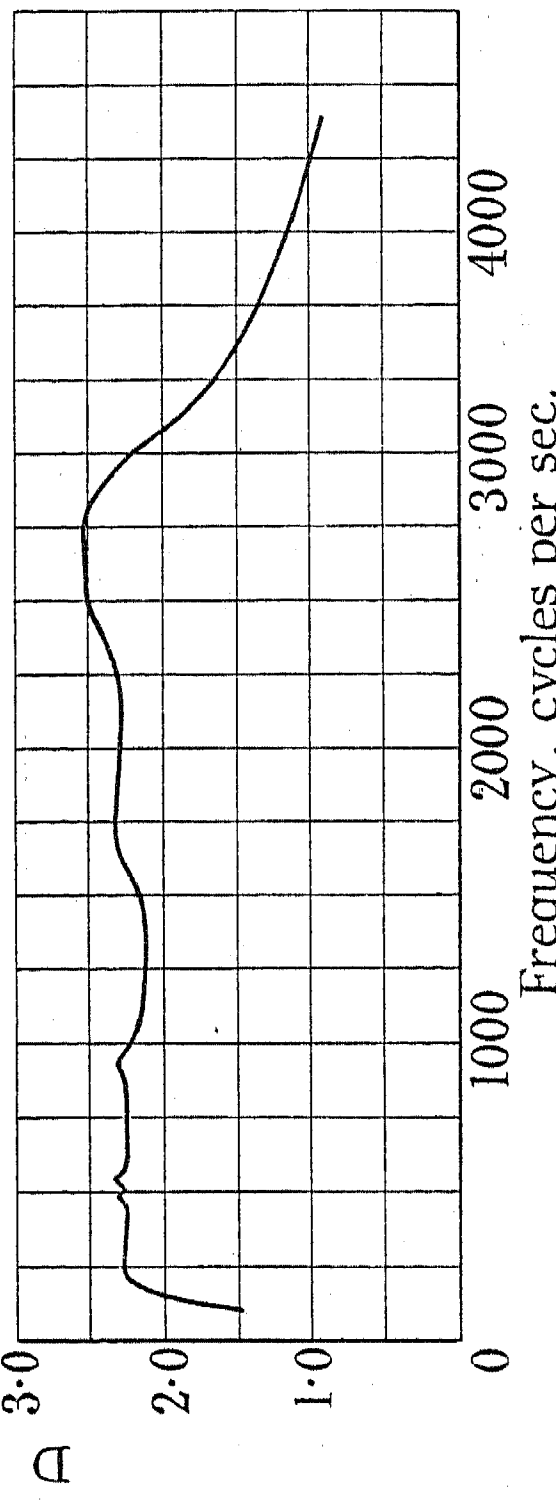


FIG. 13.

FIGS. 7 TO 13. (See Table 12.)

of about 0.25 mA. Two curves only are drawn in each illustration, since the similarity is generally such that more would be confusing.

The modifications include changes of diaphragm, filling the cavity behind the diaphragm with wax, and variations of spacing distance between diaphragm and ear-cap and of the depth of the pole-faces below the clamping surface. A record of the different conditions to which the curves of Figs. 7 to 11 apply is shown in Table 12.

Fig. 7.—The decay factor with diaphragm B (9.3) is 410 at the resonant frequency 1 100 cycles per sec.; that with diaphragm C (11.5) is 310 at 1 170 cycles per sec. In each case at higher frequencies there is an irregularity in the curve due to the two-diameter mode of vibration of the diaphragm, followed by resonance at the single-circle mode of vibration. That the frequencies at these modes of vibration are proportionately higher for C (11.5) than for B (9.3), by comparison with the frequencies at the fundamental modes, is mainly due to the fact that stiffness due to the air on each side of the diaphragm adds to the stiffness factor of the diaphragm at the fundamental mode. At the higher modes there is simultaneous displacement in both directions at different parts of the surface of the diaphragm, and consequently the added stiffness due to the air cavities is small. Diaphragm C (11.5) is not only thicker than B (9.3) but the steel has also a greater elastic modulus (cf. Table 4).

Fig. 8.—The full curve (stallo diaphragm, 0.0102 in. thick) may be regarded as typical of this type of receiver as used in practice; the decay factor is 380 at 1 125 cycles per sec. The thinner diaphragm (0.0083 in.) gives a decay factor of 410 at 1 115 cycles per sec. The influences of the two-diameter and single-circle modes of vibration are also evident in these curves. The slight rise in the curves near 4 000 cycles per sec. may be caused by acoustical effects of a kind which would be particular to the shape of the cavities in front of the diaphragm; this effect would not necessarily represent accurately the condition when the receiver is held to a real ear. In any case little is known of the accuracy of matching of the artificial ear to the real ear at frequencies above about 3 000 cycles per sec., but the curves have been continued to higher frequencies so that comparison can be made on a common basis.

Fig. 9.—The projections at the clamping surfaces of two ear-caps were cut down to 0.02 in. and 0.01 in. respectively. With the former the decay factor is 490 at 1 200 cycles per sec. and with the latter it is 630 at 1 140 cycles per sec. The reduction of the spacing gap between diaphragm and ear-cap tends to reduce the cavity volume in front of the diaphragm, and thus to produce a tighter coupling to the ear. At the same time the greater constriction for the radial displacement of air in the gap increases the mechanical resistance.

Some voice-ear comparison tests made on this receiver showed that the "volume efficiency" of the receiver with the 0.02-in. spacing was nearly the same as that with the standard ear-cap (0.045-in. spacing), but with the 0.01-in. spacing it was nearly 1 db worse. The test refers to loudness of transmission without reference to the quality.

Fig. 10.—The contrast between the normal ear-cap

and that with the 0.01-in. spacing is shown for the receiver with a heavy filling of wax behind the diaphragm. There is now constriction behind the diaphragm for both curves, and the slightly greater sensitivity with the smaller spacing may be due to tighter coupling of the diaphragm to the ear or to clamping differences.

Voice-ear tests were made on the filled receiver with the normal ear-cap, for both "volume" and "articulation efficiency," by comparison with standard receivers on the standard circuit.* While the volume efficiency was about 8 db worse, the articulation efficiency was, if anything, slightly better than standard; it is, however, known that the receiver alone accounts for a small proportion only of the loss of articulation on the standard telephone circuit.

Fig. 11.—For these curves the depth of the pole-faces below the clamping surface was increased by 0.005 in. and decreased by 0.005 in., respectively, from the normal of 0.014 in. The actual air-gaps were, as shown in Table 10, 0.0165 in. and 0.004 in. respectively. That so large a change of air-gap should cause so small a change of sensitivity was considered remarkable, and the matter was further investigated, as has been recorded in Section (9).

Voice-ear tests showed that the volume efficiency of the receiver was scarcely increased at all by the change from the normal to the smaller air-gap, and was lowered by about 0.5 db by the change from normal to the larger air-gap.

Additional information, not shown on these curves, has proved that, within wide limits, the sensitivity of a receiver as used on an ear is practically independent of the size or shape of the aperture in the ear-cap. Clearly the aperture can be quite small before effects due to viscosity at the edge become pronounced. On the other hand, if the aperture is unduly enlarged the volume of the cavity between the diaphragm and the ear is enlarged, i.e. the coupling is somewhat relaxed. An appreciable loss of sensitivity was noticed when a receiver of the handset type was tested using an ear-cap with an enlarged aperture ($\frac{1}{4}$ in. diameter); it was further noticed that the peak at the single-circle mode of vibration was much less damped.

It is of interest to compare the sensitivity of a receiver, as recorded by the frequency characteristic, with that estimated from the measurements of flux, pull, and mechanical impedance. Take, for example, the handset-type receiver with diaphragm A (10.2), the air-gap being about 0.0105 in.

If it be assumed that the alternating flux in the air-gap has a similar distribution to that of the steady flux, the effective area of the pole-faces may be taken as $A = 0.175 \text{ cm}^2$ (Table 7). This area is required to calculate force from measurements of flux (Φ) from the formula

$$\text{Force} = \frac{\Phi^2}{8\pi A} \text{ (dynes)} \quad (10)$$

Thus when the steady flux is Φ_0 and the alternating flux is $\hat{\Phi} \sin \omega t$, the alternating force is given by

* See B. S. COHEN: *Journal I.E.E.* 1928, vol. 66, p. 165.

Force

$$= \frac{1}{8\pi A} (\Phi_0 + \hat{\Phi} \sin \omega t)^2$$
$$= \frac{1}{8\pi A} \left(\Phi_0^2 + \frac{\Phi^2}{2} + 2\Phi_0\hat{\Phi} \sin \omega t - \frac{1}{2}(\hat{\Phi})^2 \cos 2\omega t \right) \quad (11)$$

so that the r.m.s. component of force at the applied frequency is

$$F = \frac{\Phi_0\Phi}{4\pi A} = \frac{800\Phi}{2 \cdot 2} \quad (12)$$

where Φ is the r.m.s. value of the alternating flux, for 1 mA current in the receiver.

The diaphragm will be regarded as an equivalent piston whose area is $A_p = 5.9 \text{ cm}^2$ (see Appendix), vibrating with r.m.s. velocity v . If Z is the total mechanical impedance of the diaphragm, including that due to the air on each side, then

$$F = Zv \quad (13)$$

From the definition of acoustical impedance, the pressure generated on the ear is

$$p = Z'_A A_p v \quad (14)$$

where Z'_A is the acoustical impedance of the cavity between receiver and ear.

Thus the sensitivity, in dynes per cm^2 per mA, is:—

$$\text{Sensitivity} = \frac{A_p Z'_A \cdot F}{Z}$$
$$= \frac{2\,150 Z'_A \Phi}{Z} \quad (15)$$

from equation (12).

Values of Φ are obtained from Fig. 5, and Z and Z'_A are calculated from the equations in the Appendix with

TABLE 13.
Comparison between Estimated and Measured Sensitivities.

Frequency, cycles per sec.	Φ	Z'_A	Z	Sensitivity	
				Estimated from Eq. (15)	Measured from Fig. 8
350	1.84	75	9 550	31	24
750	1.64	47	3 150	52	44
1 125	1.52	32.5	400	270	250
1 600	1.42	23	2 600	27	35

the data given therein and in Tables 2 and 4. Comparison is made at a few frequencies with the sensitivity measured by the frequency-characteristic test in Table 13.

Agreement is closest at the frequency of resonance; it was in the neighbourhood of this frequency that the measurements of mechanical impedance were made.

Fig. 12.—In this illustration two frequency characteristics are shown for an ear-piece receiver of the type described in Section (2). Either of two kinds of diaphragm may be supplied with the receiver; one is of

stalloy 0.011 in. thick (the full-line curve), and the other is of tinfoil 0.004 in. thick (the broken curve). The latter is of only one-half the weight of the former and has therefore superior mechanical properties, but it is magnetically less efficient and very little response was obtained from it at frequencies above about 2 400 cycles per sec.

Fig. 13.—That a flat frequency characteristic can be obtained from a receiver over a wide frequency range is shown by the curve in this illustration. This curve was obtained from an ear-piece receiver of the same type—using the stalloy diaphragm. The receiver was filled with wax just covering the pole-faces, and the spacing distance of the ear-cap was reduced to 0.01 in. The improvement is of course obtained at the expense of sensitivity; in effect the diaphragm is made to resonate at a high frequency, and severe acoustic damping is imposed by the constricted space within which it vibrates.

(12) NON-LINEAR DISTORTION AND AMPLITUDE DISTORTION.

Distortion due to overloading may be studied from theoretical considerations, but when, as in the case of telephone receivers, different kinds of overloading can operate simultaneously, the manner in which they combine to produce the resultant effect must be taken into account, and analysis becomes tedious. Certain limits to the power-handling capacity of a receiver may, however, be noted with reference to the handset receiver, for which the available data are most complete.

The sound pressure on the ear per mil r.m.s. amplitude of displacement at the centre of the diaphragm can readily be calculated. It is, for example, about 1 500 dynes per cm^2 at 200 cycles per sec., 3 000 at 500 cycles per sec., and 3 500 at frequencies above about 1 000 cycles per sec., for the fundamental mode of vibration. Overloading of the receiver due to mechanical causes is hardly to be expected at this amplitude, and the pressures are near the threshold of feeling.

From equation (11) it is seen that, even with an ideal magnetic circuit, a second harmonic is introduced whose ratio to the fundamental is $\hat{\Phi} : 4\Phi_0$. For the handset receiver, Φ_0 is about 800 and $\hat{\Phi}$, at low frequencies, about $2\sqrt{2}$ lines per mA, so that the second harmonic would be rather less than 0.1 per cent per mA. Actually, however, as mentioned in Section (9), there is evidence that the reluctance of the magnetic circuit is not quite constant for different magnitudes of the applied current.

The increase of steady flux due to an inward displacement of the diaphragm is slightly greater than the decrease due to an equal displacement outwards. On the other hand it has been shown, in Section (9), that the alternating flux is reduced as the air-gap is decreased. These two effects have been observed by steady-state measurements, but the tendency for the one to compensate the other probably applies also to instantaneous values of displacement of the vibrating diaphragm.

A few measurements have been made of non-linear distortion and amplitude distortion introduced by typical receivers of the handset and ear-piece types.

Non-linear Distortion—Use was made of a harmonic

analysing set, designed by Mr. J. F. Doust, for measuring the harmonics produced by receivers. The set employs the "beat-frequency" method, a searching tone from a heterodyne oscillator being added to the wave to be analysed, so that the fundamental and individual harmonics can be measured separately. Harmonics smaller than 0.5 per cent can be measured, but the accuracy of the non-linear distortion measurements was limited by the purity of the wave supplied, and by distortions produced by other parts of the apparatus.

Not only should the wave-form of the current supplied to the receiver be pure, but appreciable non-linear distortion should not be introduced by the artificial ear and its amplifier. Evidence was obtained to support the con-

TABLE 14.

Non-linear Distortion by Telephone Receivers.

Test condition	Current in receiver, mA	Harmonics (per cent of fundamental)			
		2nd	3rd	4th	5th
188 cycles per sec.	Calibration	1.2	3	0.4	0.6
Handset receiver	{ 43	14	—	1.4	3
	{ 12	7	—	2	3.5
	{ 1	—	—	—	—
Ear-piece receiver	{ 18	9	—	—	—
	{ 3	—	—	—	—
550 cycles per sec.	Calibration	1	1	—	—
Handset receiver	{ 6	9*	—	—	—
	{ 3	3	—	—	—
	{ 0.8	—	—	—	—
Ear-piece receiver	{ 12	3	—	—	—
	{ 3.3	—	—	—	—

* Varying, presumably because of slight changes of the frequency of resonance (1 100 cycles per sec.).

clusion, reached by calculation, that non-linear distortion produced by the condenser transmitter in the artificial ear was quite negligible. The output from the amplifier was limited to a small value in order to reduce non-linear distortion to a minimum, but the frequency characteristic (Fig. 2, curve ii) is such that, at low frequencies of the fundamental, the harmonics are somewhat exaggerated.

A few measurements were made at frequencies of 188 and 550 cycles per sec. on a receiver of the handset type (Fig. 8, full-line curve) and on the filled ear-piece receiver (Fig. 13), and the results are shown in Table 14. A calibration was first taken of the harmonics present in the complete electrical circuit; then the acoustic link (receiver and artificial ear) was introduced and the harmonics were measured again. Unless a harmonic exceed *twice* the magnitude found for the calibration it is not recorded in Table 14, since the manner in which it adds to or subtracts from that which is already present is unknown. The

blanks in the table do not mean that harmonics were not measured, but that the measured value was less than twice the calibration value.

In the case of the ear-piece receiver, since the frequency characteristic is substantially uniform the non-linear distortion is directly measured, but with the handset receiver it is distorted by the frequency characteristic. The 5th harmonic at 188 cycles per sec. and the 2nd at 550 cycles per sec. are near the main resonant frequency, and the harmonics are therefore greatly exaggerated. This effect should be allowed for in assessing the non-linear distortion, since it is, in reality, a frequency distortion.

Amplitude Distortion.—Measurements of the sensitivity of handset and ear-piece receivers with different input currents gave the results shown in Table 15, wherein the sensitivities are quoted relatively to the sensitivity with 1 mA in the receiver.

It is interesting to note that, whereas the distortion tends to increase somewhat at higher frequencies for the handset receiver, it decreases at higher frequencies for the ear-piece receiver. The order of magnitude of the distortion is similar to that observed for the alternating

TABLE 15.

Amplitude Distortion by Telephone Receivers.

Current, mA	Relative sensitivity					
	Handset receiver			Ear-piece receiver		
	(cycles per sec.)			(cycles per sec.)		
	188	750	2 000	188	750	2 000
0.25	0.96	0.92	0.94	0.91	0.93	0.93
1	1	1	1	1	1	1
4	1.08	1.15	1.13	1.25	1.13	1.1
16	1.2	1.3	1.38	1.6	1.4	1.23

flux in the handset receiver (Section 9). It may be, therefore, that the distortion is mainly accounted for by variations of the reluctance of the magnetic circuit.

(13) CONCLUSIONS.

It was not expected that the investigations would reveal any very promising line of development for the improvement in the design of telephone receivers, since the evolutionary process of design and comparison test has been in operation for so long. Yet with the advent of the new handset-type receiver, which is now a Post Office standard instrument, the opportunity arose for determining, by objective measurement, the main factors affecting the performance of this instrument. The orders of magnitude of the principle quantities involved have now been ascertained, and also the effects produced by simple modifications thereto. Although the validity of the simple theory of operation has been very substantially

confirmed, it must be admitted that some unexpected results were obtained.

So far as the sensitivity of a receiver is concerned, it appears that, with the very adequate magnet strength now available, quite wide variations from the normal of air-gap or magnet strength produce very little change, an increase in the steady flux being offset by an increase in the reluctance to alternating flux, and vice versa.

In order to obtain greater sensitivity from a receiver constructed in this manner, it would seem desirable to obtain diaphragms capable of carrying greater flux for the same mass per unit area, or of carrying the same flux with a smaller mass per unit area. Steel B shows a very slight improvement over stalloy in this respect. The optimum diaphragm thickness is also a compromise between small mass and large flux-carrying capacity.

Other dimensions involved, e.g. area of diaphragm and shape and size of the pole-faces, are also a matter of compromise between opposing influences, so that the designer is given considerable latitude (especially if he is using a strong magnet). On the other hand, if an absolute maximum of sensitivity is sought, it is difficult to make sure that all the different compromises are simultaneously adjusted satisfactorily.

With regard to quality of performance, the most serious distortion is the frequency distortion due to mechanical resonance of the diaphragm. In telephone uses this is not very serious among the total distortions present, and it is permitted for the sake of sensitivity. The frequency of resonance can be controlled within wide limits, e.g. by variations of the cavity volume behind the diaphragm.

The extent of resonance—as measured by the decay factor—can also be controlled by applying suitable damping. The effect of so doing by modification of the ear-cap is illustrated in Fig. 9; similar effects can be produced by means of a damping plate behind the diaphragm (e.g. a sheet of paper, about 1 in. diameter, cemented over the pole-faces).

The present paper is not concerned with the question of what are the most suitable frequency of resonance and decay factor for any particular usage of the receiver.

The measurements which have been made of the magnitudes of the distortions by telephone receivers due to overloading, when considered in conjunction with the information obtained by Massa,* confirm the generally accepted view that, for all ordinary uses of the receiver, the distortions are so small as to produce a negligible effect on the ear.

The authors desire to acknowledge their indebtedness to the Engineer-in-Chief of the Post Office for permission to publish the results of these investigations.

APPENDIX.

The purpose of this Appendix is to state the equations applicable to the mechanical impedance of a receiver diaphragm when used on the artificial ear. The method and notation of Chapter IV of "Acoustical Engineering" are followed.†

Consideration is restricted to frequencies at and near

* F. MASSA: "Permissible Amplitude Distortion of Speech in an Audio Reproducing System," *Proceedings of the Institute of Radio Engineers*, 1933, vol. 21, p. 682.
† Sir I. Pitman and Sons, Ltd. (London, 1932).

the main resonant frequency of the diaphragm, since such frequencies only were used for the mechanical-impedance measurements of Sections (4) and (5).

The total impedance of the diaphragm is the sum of Z_M , the mechanical impedance of the diaphragm (i.e. of its "equivalent piston") *per se*; Z'_M , the mechanical impedance due to the cavity formed by the ear in front of the diaphragm; and Z''_M , the mechanical impedance due to the cavity behind the diaphragm. Thus

$$Z_M = R_M + j(\omega m - s/\omega) \quad (16)$$

where R_M = equivalent mechanical resistance, m (grammes) = equivalent mass, and s (dynes per cm) = equivalent stiffness factor of the diaphragm—which quantities it is required to evaluate.

$$Z'_M = A_p^2 Z'_A = A_p^2 \rho c \frac{\sigma - j(kQ')}{\sigma^2 + (kQ')^2} \quad (17)$$

where Z'_A = acoustical impedance in front of the diaphragm, and A_p = equivalent piston area. (From the theory of the clamped plate, $A_p = \frac{1}{3}$ the exposed diaphragm area = 5.9 cm²);

ρ = density of air (0.0012 gramme per cm³);
 c = velocity of propagation (34 000 cm per sec.);
 $k = \omega/c$;

σ = resistance area of the artificial ear (see Table 2); and Q' = cavity area in front of the diaphragm, made up by 2.8 cm³ between diaphragm and aperture of the ear-cap, plus 3.0 cm³ in the artificial ear. Thus $Q' = 5.8$ cm³. Also

$$Z''_M = A_p^2 \rho c \frac{-j}{kQ''} \quad (18)$$

when acoustical resistance behind the diaphragm is reduced to negligible proportions. The cavity volume Q'' of the receiver was varied by fillings of wax.

For the purpose of evaluating m and s , the resistance components are ignored as a simplifying approximation. Hence if $\omega = \omega_0$ at resonance of the diaphragm when there is a wax filling leaving a cavity volume Q'' ,

$$m\omega_0 - \frac{s}{\omega_0} - \frac{A_p^2 \rho c^2}{\omega_0} \left(\frac{1}{Q'} + \frac{1}{Q''} \right) = 0 \quad (19)$$

$$\text{i.e.} \quad m\omega_0^2 = s + 8.3 \times 10^6 + \frac{48.2 \times 10^6}{Q''} \quad (20)$$

The resistance component R'_M , due to the artificial ear, is

$$R'_M = \frac{A_p^2 \rho c \sigma}{\sigma^2 + (kQ')^2} \quad (21)$$

It was found convenient to plot a curve of R'_M against ω for evaluating R_M from the decay-factor measurements.

In ignoring effects of the *shape* of the cavities Q' and Q'' , it is assumed that there are no constrictions and that all linear dimensions are small compared with a wavelength. The largest linear dimension is the diameter of the diaphragm; as the wavelength is reduced to values approaching, say, twice the diameter, uniformity of pressure within the cavities may no longer be assumed.

PRINCIPLES OF AUDIO-FREQUENCY WIRE BROADCASTING.

By P. P. ECKERSLEY, Member.

(Paper first received 9th November, 1933, and in revised form 16th January, 1934; read before the WIRELESS SECTION 11th April, 1934.)

SUMMARY.

The quantitative limitations of wireless broadcasting have stimulated an interest in alternative methods of distributing programmes to listeners. Wire broadcasting has certain basic technical and economic advantages over wireless broadcasting. Wire-broadcasting technique has been extensively applied in Holland, where 50 per cent of the Dutch listeners have their programme service laid on to the house by a wire connection. Relatively slight developments of the same nature have taken place in Great Britain.

"Audio-frequency rediffusion" is the most common form of "wire broadcasting" existing to-day. In "audio-frequency rediffusion," programmes originally transmitted by "wireless" are picked up by a receiver located where reception conditions are favourable, and the output of this receiver is connected, usually by landline, to the input of an amplifier which raises the level of the receiver output to a value sufficient to energize at once a thousand or more loud-speakers connected to the amplifier by a conducting network.

In common practice this network is supported on house chimneys, but sometimes it is carried on poles. The consumers' branch feeders are wired in lead-covered cable.

The paper analyses the effects set up by the interaction of the reactances and resistances composing the network and the loud-speakers, and it shows that the received level, particularly towards the ends of the lines, varies enormously both with loading at certain audio frequencies and with audio frequency for a given loading.

Certain generalized rules are laid down to indicate how the distortions incidental to this form of wire broadcasting may be partly minimized or wholly eradicated.

The analysis of the network performance allows the preparation of a specification for the amplifier necessary to supply power to the network.

INTRODUCTION.

It is well known that too few wavelengths are available for the purposes of wireless broadcasting. This makes it impossible to give all listeners both a variety of choice of programme and good-quality reproduction. It has been shown, for example, that it is impossible to give more than one clearly heard and properly reproduced programme to every European listener.*

If programmes were distributed to listeners by wires none of these difficulties would arise; therefore wire broadcasting has great importance. It has already begun to take form in Europe, particularly in Holland.

This paper discusses the technical principles of the method. It deals in very general terms with all forms of wire broadcasting, but in particular with "audio-frequency rediffusion" as practised to-day.

DEFINITIONS.

The component parts of a wire broadcasting system are (1) a network, (2) transmitters or amplifiers, and (3) reproducers or selectors (located in consumers' houses).

The transmitters or amplifiers inject currents into the network at one point, and these currents are conducted to all points on the network. Reproducers or selectors connected to any part of the network appreciate these currents and thus create audible sounds.

There are two main distinctions between different methods adopted to set up a wire broadcasting system, called respectively "audio-frequency wire broadcasting" and "carrier-frequency wire broadcasting."

In audio-frequency wire broadcasting the disturbances are composed of alternating currents having any frequency within the gamut of audible sound and are therefore suitable to energize directly any loud-speaker physically connected to the network. In carrier-frequency systems the disturbances fed into the network are composed of alternating currents having frequencies higher than the audible range (say, 20 kilocycles per sec.) the intensity of which is modulated by audio frequency.

In carrier-frequency systems the consumers' apparatus must embody a rectifier.

A carrier-frequency wire-broadcasting system can best be set up by using the electric light and power network as the vehicle to carry the high-frequency currents between transmitter and consumer. This in no way interferes with the primary function of this network, i.e. to distribute electric power to householders.

An audio-frequency wire-broadcasting system might be set up by using an existing telephone network, but if this were done it would be necessary to use an amplifier in each consumer's house. The level required to energize a loud-speaker direct is so much greater than the level required to operate the telephone receiver that, unless the former level is reduced and then amplified in the consumer's premises, the broadcasting service would seriously interfere with the telephone service.

It is common practice, when setting up an audio-frequency wire-broadcasting service, to construct a new network. This can be done either by burying cable or by suspending wires from house chimneys or poles, i.e. making an overhead network. Buried and overhead networks may be combined.

The cost of setting up a wire-broadcasting system is much the same whichever of the methods described above is adopted, because where existing networks can be utilized the consumer's apparatus is relatively complex, but where the consumer's apparatus is simply a loud-speaker new networks must be constructed.

* P. P. ECKERSLEY: "Required Minimum Frequency Separation between Carrier Waves of Broadcast Stations," *Proceedings of the Institute of Radio Engineers*, 1933, vol. 21, p. 193.

Wire-broadcasting systems could be extended and interlinked so that every householder in a given country or continent could get a programme service, and wireless broadcasting would, in that event, be unnecessary. The capital cost of installing such a system would, however, be enormous. Wire-broadcasting systems are at present remunerative only when the "wired" houses are close together.

Rediffusion is a particular application of wire broadcasting which owes its existence chiefly to the fact that the ordinary methods of wireless broadcasting often fail to give a trouble-free and silent background service. This latter disadvantage of wireless broadcasting is more pronounced in densely populated areas, where rediffusion is most practicable.

In rediffusion practice a wireless receiver is set up in a locality as free as possible from electrical interference, probably outside the urban boundaries. The output from the receiver is taken, usually via a telephone line, to premises chosen to be in the midst of the densely populated area to be served by "rediffusion." Amplifiers (or transmitters) installed at this point raise the level or change the character of the disturbances coming in from the remote receiver. The feeders of the network are connected to these amplifiers or transmitters at one point and conduct the output to consumers' houses scattered throughout the area served. The "wireless" programmes are thus "rediffused" by wire, by either carrier-frequency or audio-frequency technique.

AUDIO-FREQUENCY REDIFFUSION.

Nearly all rediffusion systems in existence use the audio-frequency principle and employ an overhead network. In Holland, however, where the authorities are more sympathetic to wire-broadcasting technique than in Britain, a few of the larger exploiting companies are finding it possible to install buried cable for the main feeders. This practice has obvious technical and æsthetic advantages.

It appears probable that overhead networks will have to be used in this country for some time to come, because the cost of burying cable in this country is very high. It is therefore worth while to examine what distortions are set up when overhead networks are used, and how it is possible to correct or minimize the unwanted effects caused by the interactions of the reactances and resistances of the network and the loud-speakers.

The network is made up of a number of feeders which run out in different directions from the place where the amplifier is located. Each feeder contains as many lines, i.e. as many pairs of wires, as there are programmes to be transmitted. "Phantom" technique has not as yet been very successful.

Not more than two programmes are usually transmitted in British practice, and so in this case one feeder contains two lines. In Holland a 3- or 4-programme service may be given, but here again there are usually as many lines as programmes sent out.

The currents in the two wires comprising a line are kept as far as possible in phase opposition so that cross-talk between the lines of a feeder, and interference with the telephone service, may be avoided or minimized.

The wires are supported on porcelain insulators, which are commonly supported by iron brackets clamped or nailed to chimneys. Long rows of houses may very

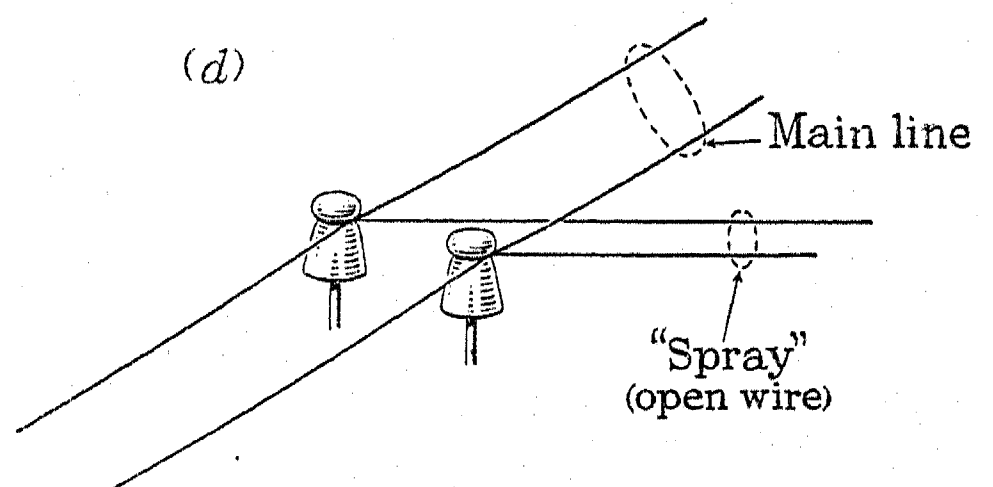
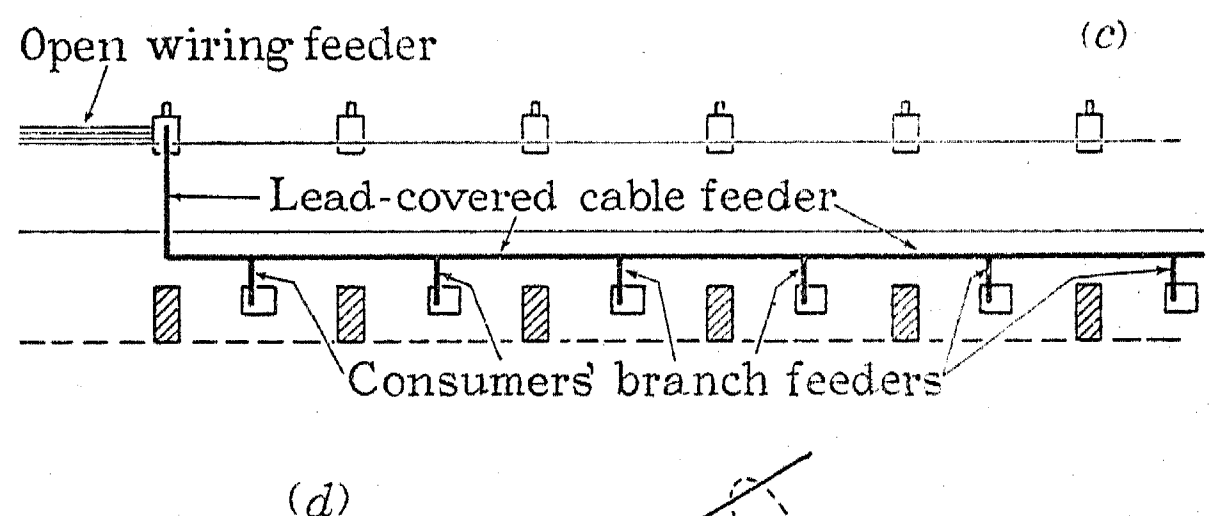
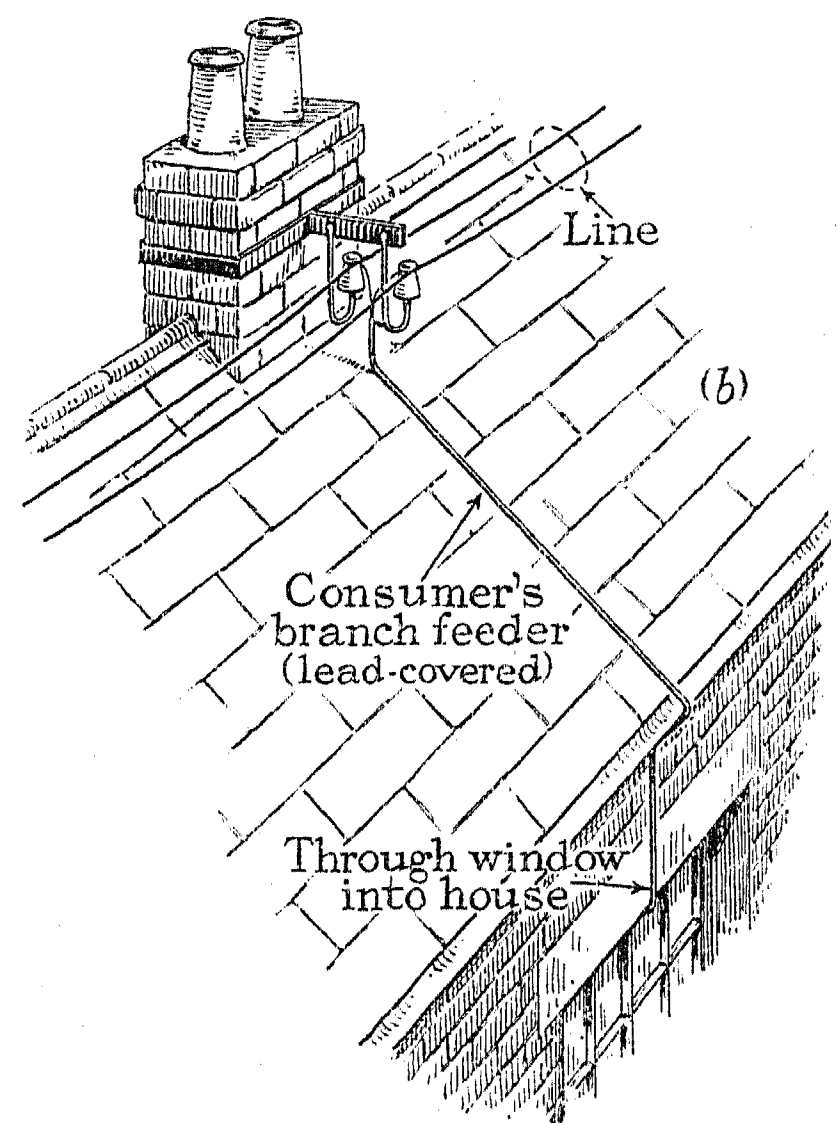
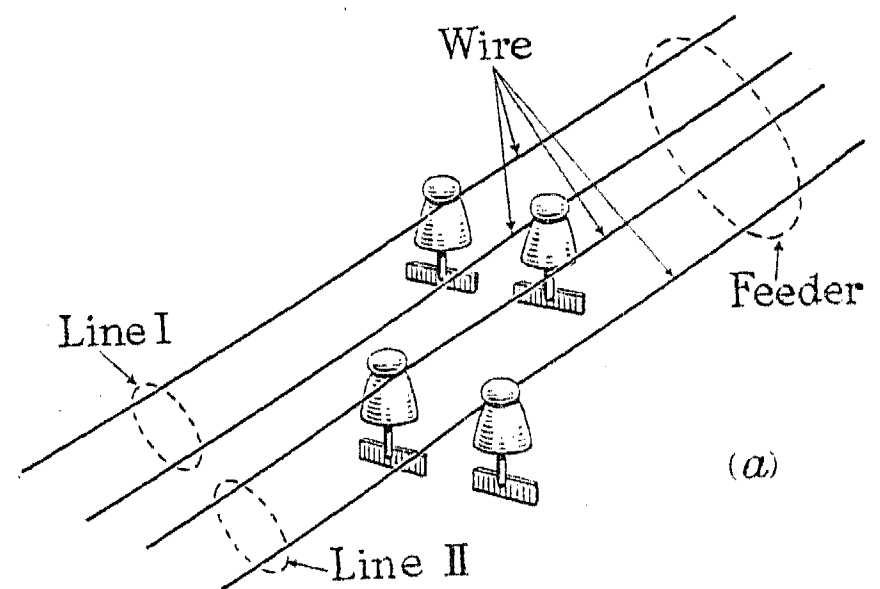


FIG. 1.

- (a) A 2-programme feeder on the open wiring system (diagrammatic).
 (b) A consumer's branch feeder teed across a line (diagrammatic). Only one line shown.
 (c) "Block" wiring teed off from open-wire feeder (diagrammatic).
 (d) Open-wire spray running from main line (diagrammatic).

well be wired in this way. Each wire is from 10 to 30 cm away from its fellow in the line. This system is described as "open" wiring, to distinguish it from "cable wiring."

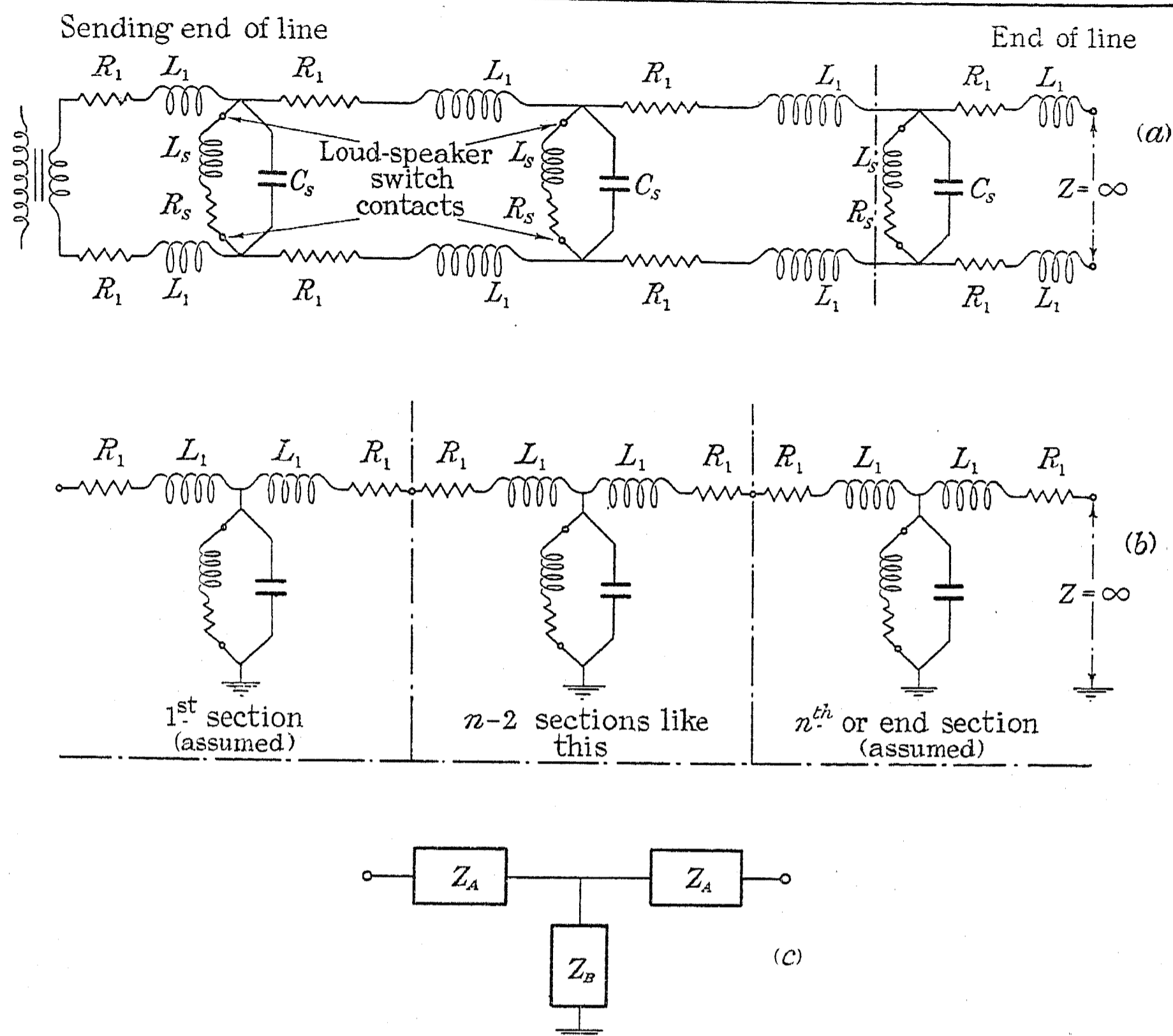


FIG. 2.—Resolution of line into electrical equivalent.

(a) Electrical equivalent of line, assuming symmetry.

R_1 = resistance of line between consumers.
 L_1 = inductance of line between consumers.
 R_s = resistance of loud-speaker.
 L_s = inductance of loud-speaker.
 C_s = capacitance of branch wiring.

(b) Electrical equivalent of (a), assuming that conditions will be undisturbed if 1st and n th sections are arranged as shown. (It is obviously fair to assume this.)

(c) Representation of a section of the line. $Z_A = 2(R_1 + j\omega L_1)$. Z_B = impedance of $L_s R_s$ and C_s as shown in (a).

The latter may be carried overhead on "messengers," or nailed to the sides of houses, or buried.

A consumer is given his service via a branch feeder made up of lead-covered cable which connects each pair of its lines across each pair of (main) overhead open-wire lines.

Sometimes as many as 10 to 15 consumers are fed from one tee-off, either by a "spray" of open wiring tee off for each consumer, or through extended lead wiring. The latter type of wiring is called "block wiring."

Each householder has a switch to switch the loud-speaker to one or the other programme or to open circuit. Some houses have lead-covered cable extension wiring from room to room.

A study of Fig. 1, combined with this description, should give a sufficiently clear picture of the system to enable the reader to follow the analysis given below. The system has, in fact, been described in some detail in order to be able to draw, in Fig. 2, the electrical equivalent of the system.

Line-Element Values.

The values of the elements of what is, in effect, an artificial line of n sections are as follows:—

Line wires	Resistance = 8.2 ohms/1 000 m
Consumers' branch feeders (of lead-covered cable)	Capacitance = 1 000 $\mu\mu\text{F}$ /10 m
Line (wires 20 cm apart)	Resistance = 16.4 ohms/1 000 m Inductance = 2 500 μH /1 000 m Reactance = 15.0 ohms/1 000 m at 1 000 cycles per sec. (about)

Loud-Speaker Constants.

It is necessary to find the effective values of loud-speaker inductance and resistance. These quantities vary with frequency. The constants shown in Fig. 3 were determined by applying an alternating (measured) voltage to a circuit made up of a variable capacitance, the loud-speaker under test, and a hot-wire milliammeter, in series with one another, and finding the value of

capacitance reactance at which resonance occurred. If the frequency of the currents is known, the inductance of the loud-speaker can be calculated. The resistance is given by dividing the voltage by the current flowing when the circuit is in resonance. The results are not reliable at very high frequencies, owing to self-capacitance effects.

Fig. 3 shows analyses of two loud-speakers, one of

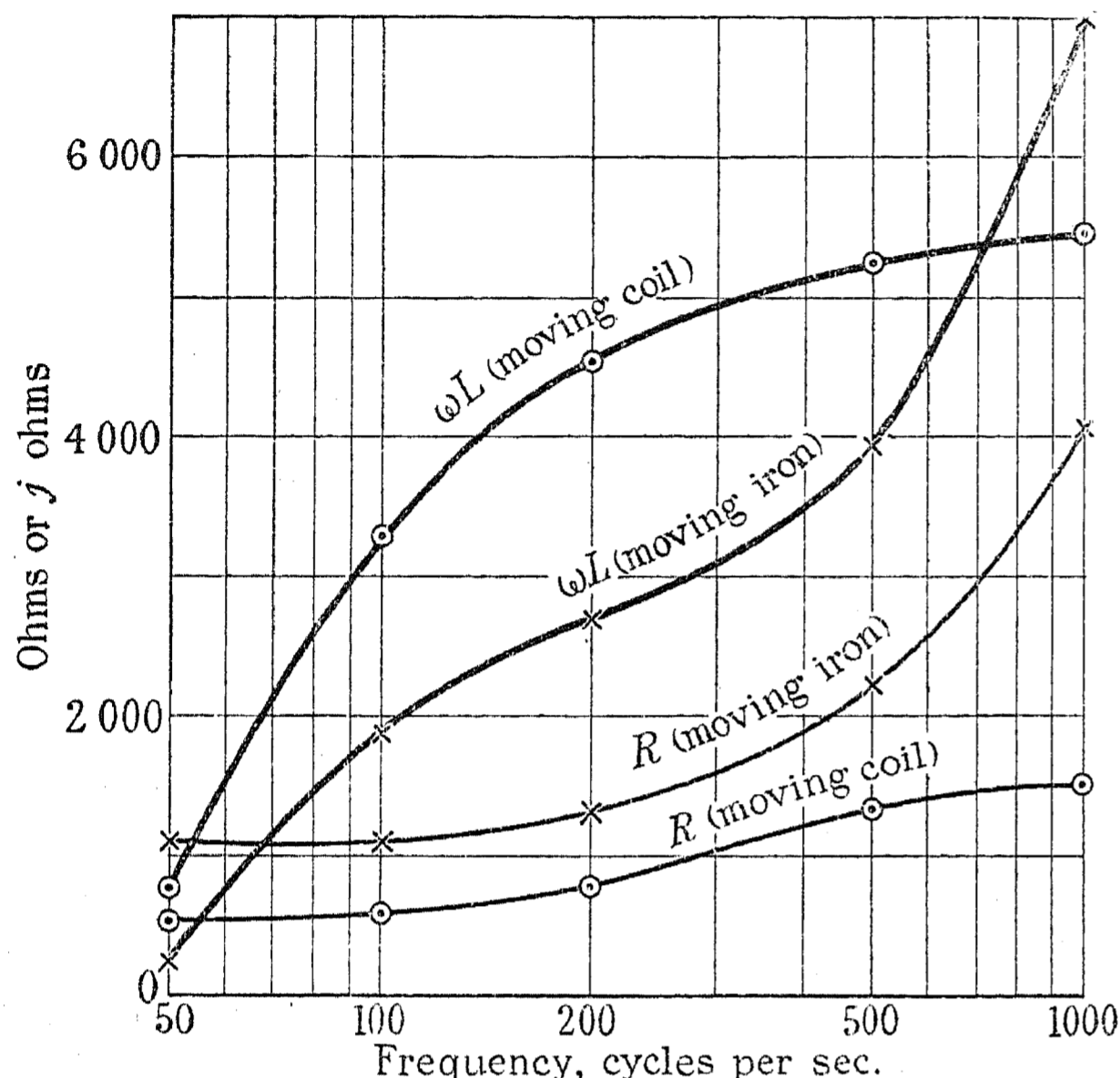


FIG. 3.—Characteristics of moving-iron and moving-coil loud-speakers.

the moving-coil and the other of the moving-iron type, both typical of those used in rediffusion systems.

ARTIFICIAL-LINE THEORY.

We are now in a position to make some calculations of the behaviour of the electrical system representing a line and having the form shown in Fig. 2.

The basic formulæ used in the analysis which follows are well known but are repeated here for the sake of completeness.

If Z_A be the impedance of the series arm of an artificial line and Z_B the shunt impedance (Fig. 2c), then if θ is the transfer constant per section

$$\cosh \theta = 1 + \frac{Z_A}{Z_B} \quad (1)$$

$$\text{Moreover} \quad \theta = \alpha + j\beta \quad (2)$$

where α is the amplitude and β the phase-change constant.

If the n th section of the artificial line, as illustrated in Fig. 2(a), is open-circuited ($Z = \infty$), the voltage V_n across this n th section is given by

$$V_n = V_0 \frac{1}{\cosh n\theta} \quad (3)$$

where V_0 is the sending-end voltage.

The effects of attenuation will be most marked at or near the end sections of a line, and so if we find V_n we

shall know, roughly, how the levels vary in other parts of the system. Indeed, formulæ exist to calculate the voltage in the r th section, where $r < n$. The formulæ given are, however, based upon the assumption that the arrangement is symmetrical; therefore the results obtained from their application can only reveal tendencies because, in practice, lines are not symmetrical. Nevertheless, the results will be shown to have great practical usefulness.

θ must vary with frequency. We can, therefore, conveniently classify θ in four categories as θ_b , θ_p , θ_s , and θ_t .

θ_b will represent conditions when the frequency is so low that all reactances may be neglected in comparison with resistances. θ_p applies to conditions when the frequency is about the value where the down-lead capacitance C_s (Fig. 2) resonates (in parallel) with the loud-speaker inductance L_s .

θ_s represents the transfer constant when the line inductance L_1 resonates (in series) with the parallel wiring capacitance C_s , the loud-speaker being assumed to be switched off the line.

θ_t is the value of θ for frequencies higher than those at which feeder inductance and block-wiring capacitance resonate.

Considerations of θ_b (loading factor).

If all reactances are neglected, we can write from (1) and (2)

$$\cosh \theta_b = \cosh \alpha_b = 1 + \frac{R_1}{R_s} \quad (4)$$

$$\text{But} \quad \cosh x = 1 + x^2/2! + \dots x^n/n! \dots$$

So that, provided R_1/R_s is not too large (and in practice it is $\ll 1$)

$$\alpha_b = \sqrt{[2R_1/R_s]} \quad (5)$$

If l is the length of a line and k a constant,

$$nR_1 = kl \quad (6)$$

so that, from (5) and (6),

$$n\alpha_b = \sqrt{[2nlk/R_s]} \quad (7)$$

In order that consumers near the end of the line may get adequate "bass" reproduction when the line is heavily loaded, V_n must never be less than a certain fraction of V_0 [see equation (3)]. Let us say that V_n must never be less than $\frac{1}{2}V_0$. Then $\cosh n\alpha_b = 2$ [see equation (3)], so that, from (7),

$$nl = R_s 0.85 \frac{1}{k} \quad (8)$$

The product nl may be described as the "loading factor" of a line. It shows that one may plan long lines with few consumers connected to them, or short lines with many, but that the product, (consumers) \times (length), must always equal some figure to be determined.

Obviously, the smaller we can make $n\alpha_b$ the better. We can decrease it by increasing R_s or decreasing k . The constant k depends upon the resistance of the wire. This cannot be decreased because a limit, determined by

the weight of wire to be supported, is reached. Chimneys are less solid than they appear, and storms destroy overhead wiring unless this has a very good factor of safety.

R_s can be increased, however, above its value represented purely as the d.c. resistance of the loud-speaker or loud-speaker transformer primary windings, by adding resistance in series with the loud-speaker or transformer primary winding.

Every loud-speaker movement has been (mechanically) designed to give good bass reproduction when working from a valve. A typical output valve is a source of voltage having an internal resistance of the order of 2 000–3 000 ohms. The internal resistance of a rediffusion line at low frequencies is of the order of tens of ohms. It is, therefore, perfectly legitimate to connect a resistance of (say) 2 000 ohms in series with the loud-speaker. Indeed, unless this is done, reproduction on a not-too-heavily loaded line may be "bass heavy." This practice greatly increases the effective value of R_s and has the further advantage of preventing the line from being short-circuited when, by accident or design, the loud-speaker terminals are short-circuited.

The effective value of R_s can, of course, be almost indefinitely increased and/or k decreased by connecting a transformer between line and loud-speaker to step-down the line voltage to the speaker, which line voltage must be correspondingly increased at the sending station to give the same power to the speaker.

This practice is not advisable when overhead networks are used, because with direct connection of speaker to line, peak voltages of about 100 volts are momentarily established between wire and wire, and any considerable increase in line voltage might endanger the lives of linemen compelled to handle the wires, particularly in wet weather. New construction and maintenance work has to go on during service hours.

We can thus take R_s to be of the order of 2 000–3 000 ohms. k is calculable from the constants already given. The next question to determine is what loading to expect on any line. Is it necessary, for example, to assume that every consumer's loud-speaker would be connected during the transmission of a very popular programme to one line, and none to the other? Practice shows that the relative popularity of one programme compared with the alternative available may be practically equal to infinity, but that at no time is a programme so popular that every consumer on a given line will listen to it at the same time. 80 per cent of the total number of consumers' loud-speakers getting service from a line may at one time be connected to that line, however. This rarely happens but must be legislated for.

Taking all these factors together, we may say that:—

Provided the loss of level at bass frequencies, i.e. around 50 cycles per sec., shall never exceed 6 decibels;

Provided no more than 80 per cent of the consumers taking service from a line connect their speakers to that line at one time;

Provided the wire used for the line has a resistance of roughly 8 ohms/1 000 m;

Provided a resistance of the order of 2 000 ohms is connected in series with typical loud-speakers; and

Provided the speakers are of the moving-iron type, then:—

The length of line in kilometres, multiplied by the number of consumers who take service from that line, must not exceed the figure 650, or the length of the line in miles, multiplied by the number of consumers, must not exceed the figure 400.

These figures are intended only as a rough guide. In practice the loading factors, calculated as above, for average rediffusion lines are of the order of 2 000 when the line length is expressed in miles! No bass reproduction results, however.

Obviously, moving-coil speakers give better results than moving-iron speakers for the same loading factor, because (see Fig. 3) the reactance of the former rises more quickly with frequency than the latter, and this analysis applies, in principle, at the frequencies where loud-speaker inductive reactance plays some part. The above figures can safely be doubled when certain types of moving-coil speakers are used.

It is doubtful, in typical rediffusion systems, where moving-iron speakers, small added loud-speaker resistances, and long and heavily-loaded lines, are used, whether consumers near or at the ends of the lines can hear the reproduction of any frequencies below 250 cycles per sec.

Considerations of θ_p .

At frequencies $\omega_p/(2\pi)$ varying between 2 000 and 5 000 cycles per sec. (depending upon the value of the shunt capacitance of the cable wiring) the inductive reactance of the loud-speaker equals the capacitive reactance of the wiring, and a parallel resonant circuit exists.

From (1) we may say that in the case of a rediffusion line (see Fig. 2)

$$\cosh \theta = 1 + (R_1 + j\omega L_1) \left(j\omega C_s + \frac{1}{R_s + j\omega L_s} \right)$$

As a very general approximation we may neglect R_1 in comparison with $\omega_p L_1$ and R_s in comparison with $\omega_p L_s$, and write

$$\cosh \theta_p = 1 - \omega_p L_1 \left[\left(\omega_p C_s - \frac{1}{\omega_p L_s} \right) - \frac{jR_s}{\omega_p^2 L_s^2} \right] \quad (9)$$

At resonance, $\omega_p C_s = 1/(\omega_p L_s)$. Furthermore, $jR_s/(\omega_p^2 L_s^2)$ is much less than 1, so that

$$\cosh \alpha_p = 1 \quad \text{and} \quad \alpha_p = 0 \text{ (nearly)} \quad (10)$$

From this we see that $V_{np} = V_0$ and there is no attenuation, or in practice the attenuation will be extremely slight.

Considerations of θ_s .

When a loud-speaker is switched off the line the parallel branch L_s, R_s (Fig. 2), is disconnected from the system and we have a simple low-pass filter connection.

We can write

$$\cosh \alpha_s = 1 - \omega_s^2 L_1 C_s$$

and see that when $\omega_s^2 L_1 C_s = 1$, i.e. when a "series" resonance takes place,

$$\cosh \alpha_s = 0 \quad \text{and} \quad V_{ns} = \infty \quad (11)$$

If the loud-speaker is still connected, then

$$\cosh \theta_s = 1 - \omega_s^2 L_1 C_s + \frac{L_1}{L_s} + j \frac{R_s \omega_s L_1}{\omega_s^2 L_s^2}$$

Both L_1/L_s and the imaginary term are small compared

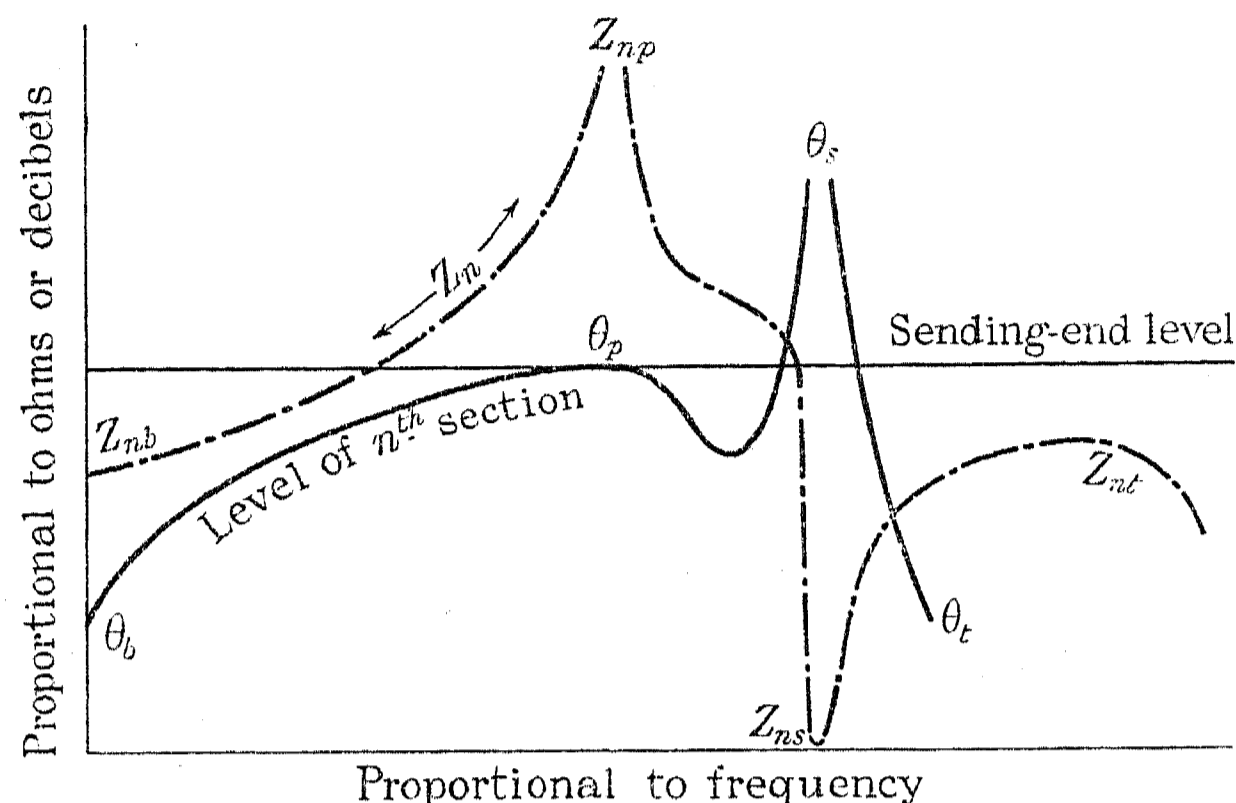


FIG. 4.—Distribution of power in sending-end impedance of a line as illustrated in Fig. 2.

with unity, but obviously the value of $\cosh \theta_s$ is greater when the loud-speaker is connected.

This means that we may expect a very large *rise* in voltage at the end of a line around the higher frequencies whatever the line loading, but that this rise will be less

Sending-end Impedance of Lines.

Associated with each transfer constant θ_b , θ_p , θ_s , and θ_t , there will be a sending-end impedance Z_{nb} , Z_{np} , Z_{ns} , Z_{nt} .

In general

$$Z_n = Z_0 \frac{\cosh n\theta}{\sinh n\theta} \quad \dots \quad (12)$$

where Z_0 , the characteristic or iterative impedance, is given by

$$Z_0 = \sqrt{[Z_A^2 + 2Z_A Z_B]} \quad (\text{see Fig. 2c}) \quad \dots \quad (13)$$

Considerations of Z_{nb} .

Obviously in this case

$$Z_{ob} = \sqrt{[R_1^2 + 2R_1 R_s]}$$

or, since $R_s \gg R_1$,

$$Z_{ob} = \sqrt{[2R_1 R_s]}$$

and

$$Z_{nb} = \sqrt{[2R_1 R_s]} \frac{\cosh na_b}{\sinh na_b} \quad \dots \quad (14)$$

We have seen that $\cosh na_b = 2$ for a maximum loading factor, when it is apparent that $\cosh na_{b_{max.}} = \sinh na_{b_{max.}}$ (nearly) and

$$Z_{nb_{min.}} = \sqrt{[2R_1 R_s]} \quad \dots \quad (15)$$

and will depend upon R_1 , which in turn depends upon the spacing between consumers.

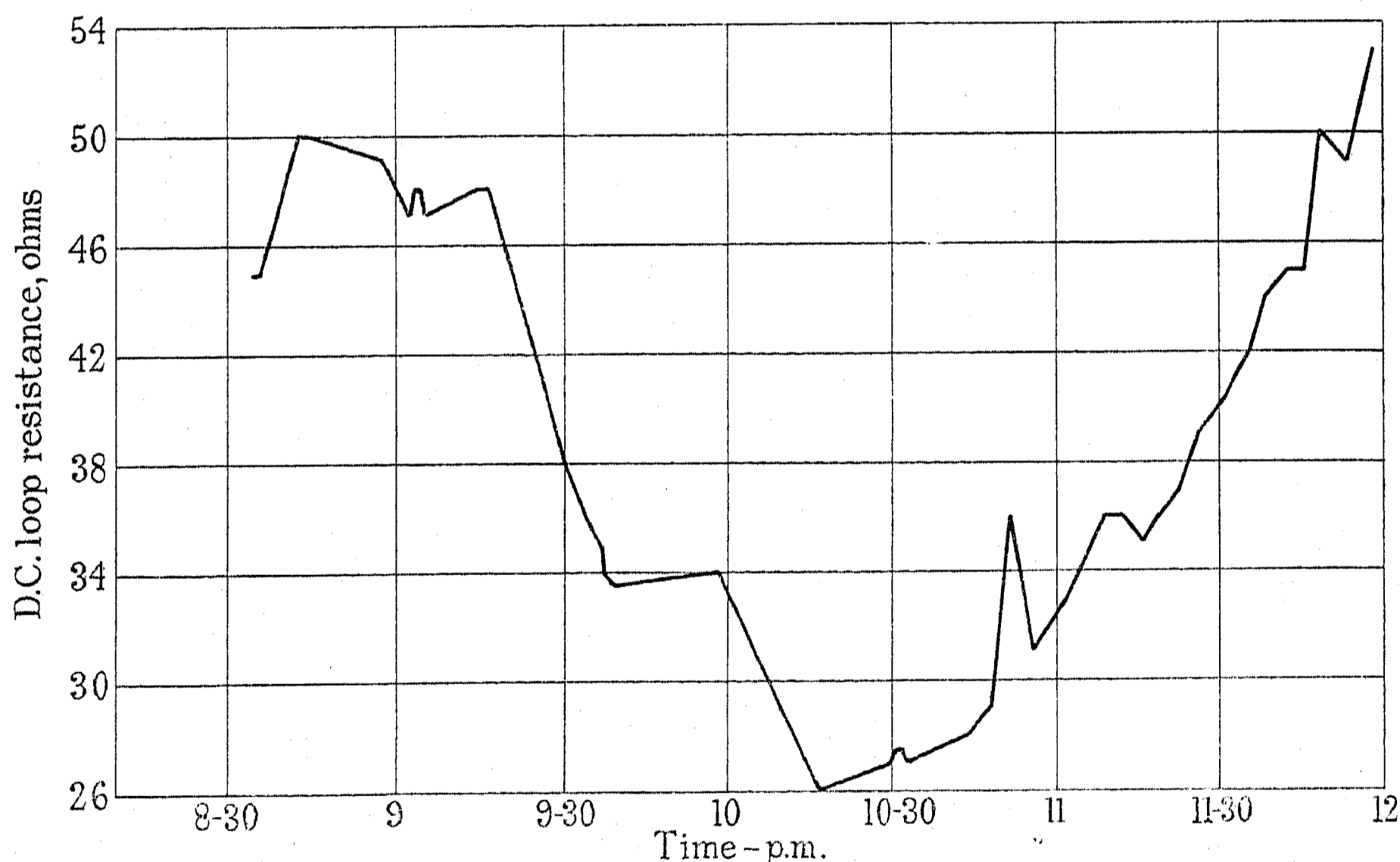


FIG. 5.—Variation of line load resistance with time.

the more loud-speakers are connected to the line, i.e. the greater the load.

Considerations of θ_t .

Treating the line as a low-pass filter we see that, above the cut-off frequency (where the series inductance of the line resonates with the capacitance of the parallel connected wiring), there will be severe attenuation.

It is obvious that R_1 cannot be less than a certain amount. It is found that Z_{nb} is seldom less than 25 ohms with normal values of R_s , i.e. with series resistances of the order of 2 000 ohms. But Z_{nb} varies enormously with na_b , hence with n , and thus with loading nl . A curve showing the value of Z_{nb} plotted against time is given in Fig. 5 for a typical line. The reciprocal of Z_{nb} is taken as an index of the popularity of a programme.

Considerations of Z_{np} .

We know that $\cosh \theta_p = 1$ at frequency $\omega_p/(2\pi)$, so that obviously [from (12)] since Z_{op} is finite and positive

$$Z_{np} = \infty \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Considerations of Z_{ns} .

Z_{ns} is obviously equal to 0 since we have seen that $\cosh \theta_s = 0$ and also since consideration shows that $Z_{os} = 0$.

Considerations of Z_{nt} .

Here the sending-end impedance is finite and becomes low at high frequencies.

Diagrammatic Summary.

Theory thus shows that the level on the outer parts of

It is apparent from artificial-line theory that these effects could be prevented or minimized if the lines were terminated by a resistance equal to the image impedance of a typical section.

Moreover, if this were done, the sending-end impedance at the critical frequency $\omega_s/(2\pi)$ would rise above its value when no terminations were applied.

It was thus suggested that all lines and sprays should be terminated by resistances. This suggestion was made before it was possible to carry out any experimental work. When this was, however, eventually carried out, as described hereunder, the theory set out above was shown to be justified in all particulars.

EXPERIMENTAL VERIFICATION OF THEORY.

If the amplifier feeding a line has its input connected to a source of pure sine-wave voltage, it is possible to

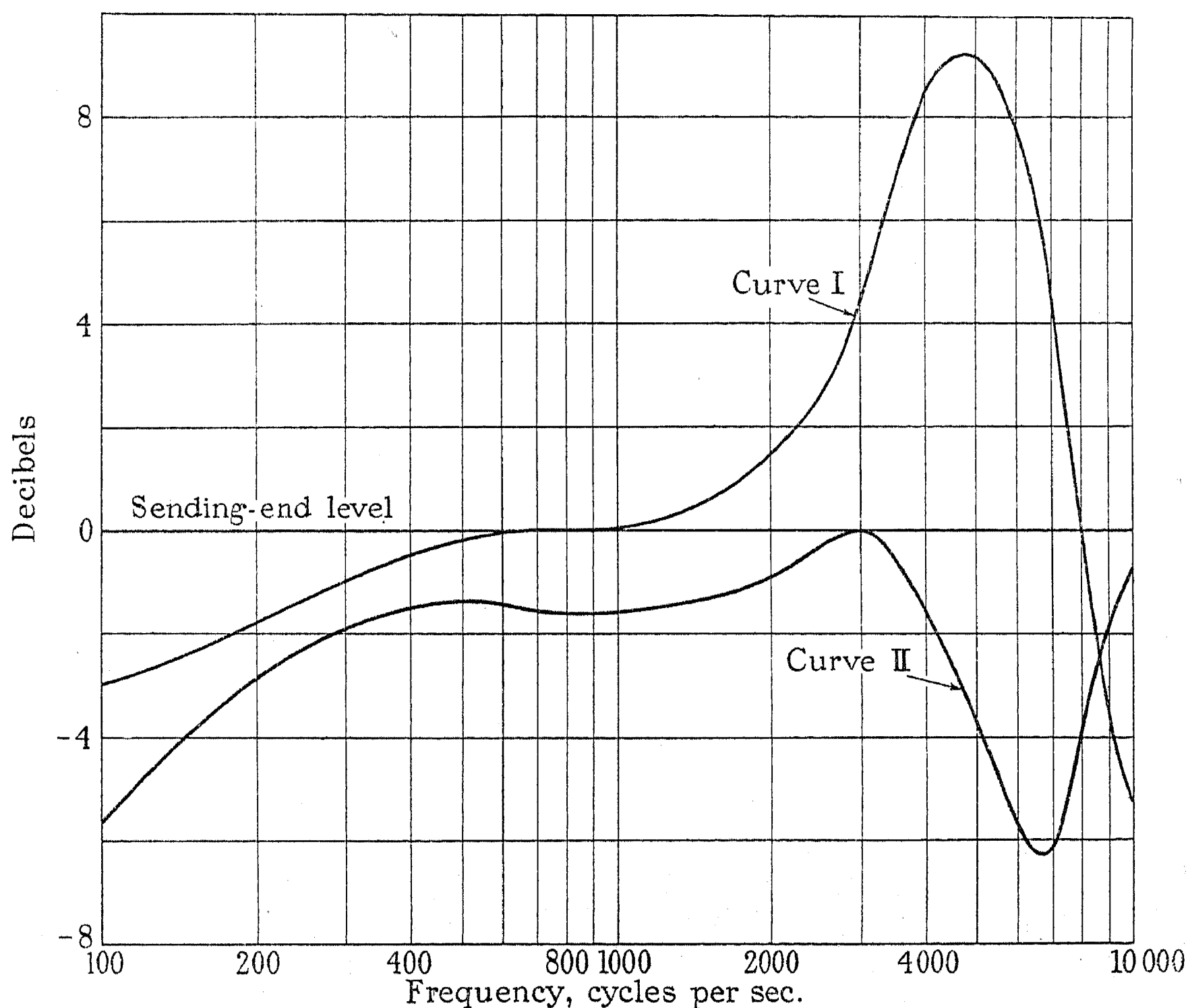


Fig. 6(a).—Comparison of two feeders having different amounts of parallel lead wiring.

Curve I.—Lightly loaded—a good deal of block wiring.
Curve II.—Medium loaded—not much block wiring.

the network and the sending-end impedance should vary as shown in Fig. 4.

Line Termination.

It has been shown that the network described behaves very differently at different frequencies. The most pronounced variations from the sending level will be due to the series resonance effects associated with the frequency $\omega_s/(2\pi)$, when the level at the end of the lines may rise considerably above the sending-end level. Moreover, the amplifiers energizing the lines would be heavily loaded at and around this critical frequency.

measure the voltage applied to the line and the resultant current fed into the line at various frequencies. This gives Z_n , the sending-end impedance.

The work is made difficult because, while measurements are being taken, the consumers will not leave their speakers connected to a line which only gives them the noise of a prolonged single note instead of the customary programme. It is necessary, therefore, during programme intervals to make a quick change-over to "squeak" input and hope that line loading will not seriously change. Directly readings are taken the programme service is restored. The d.c. sending-end

resistance of the line is continuously measured to re-check line loading. At least, consumers cannot remove the lead cabling comprising branch feeders, and so values of Z_{ns} and θ_s can be leisurely investigated after programme hours.

Several thousands of readings have been taken, notably by the author and his colleague, Mr. W. T. Sanderson, chief engineer of Nottingham Rediffusion Services, Ltd. Readings were also taken on a feeder belonging to the Broadcast Relay Service Co., Ltd., of Hull, by Mr. P. J. Adorjan, working under the author's direction.

Only a few typical curves are given here [Fig. 6, (a), (b),

and the parallel circuit is less damped, as ωL_s becomes relatively much greater than R_s .

The marked effects of line termination are clearly illustrated in Fig. 6(b), where the sending-end impedance and the level towards the end of the line are plotted on the same graph and are shown to be inverse and brought to a greater constancy by line termination.

It was found, however, that when the actual values of line terminating resistance were low enough to give substantial diminution of the resonance effects they loaded the line severely for low frequencies. This difficulty was overcome by connecting a condenser of neg-

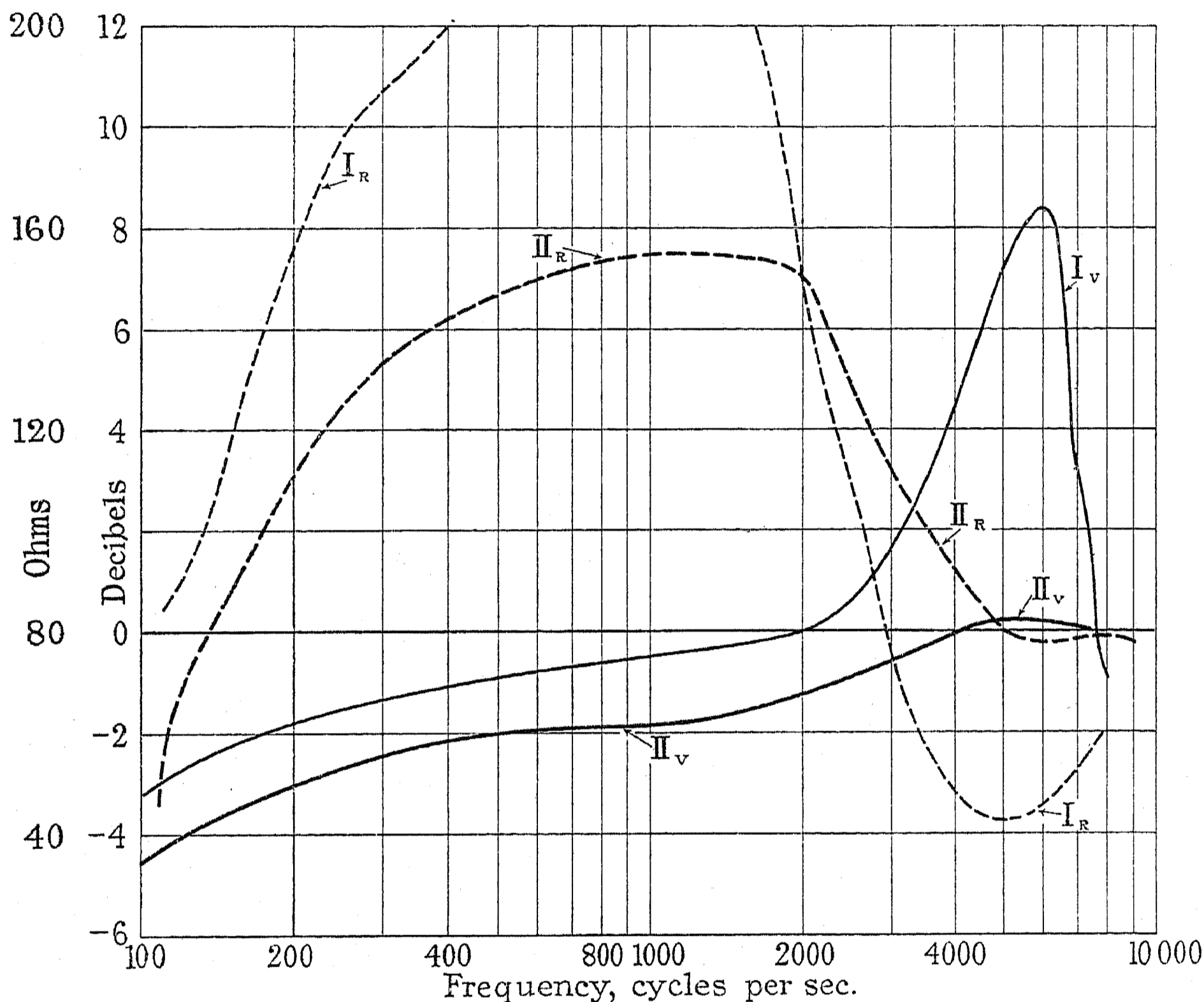


FIG. 6(b).

Curves I.—Not terminated.
Curves II.—Terminated.
Curve I_v.—Level (unterminated).
Curve II_v.—Level (terminated).
Curve I_R.—Impedance (unterminated).
Curve II_R.—Impedance (terminated).

NOTE.—No condensers were used in series with terminating resistances; Curve II_R would not fall so rapidly at low frequencies if they were used.

and (c)], but these show clearly that the conditions expected from theory are set up in practice.

It is interesting to compare the two curves in Fig. 6(a), one showing a clear case of parallel resonance and thereafter rising to give a series resonance at a frequency of, perhaps, 15 000 cycles per sec., while the other merges the conditions associated with frequencies $\omega_p/(2\pi)$ and $\omega_s/(2\pi)$ due to the higher line parallel capacitance. In nearly all cases illustrated the capacitance C_s is high and hence conditions associated with frequencies $\omega_s/(2\pi)$ are present. Where block wiring is only sparingly used, conditions associated with frequencies $\omega_p/(2\pi)$ are more evident since series resonance occurs at higher frequencies

ligible reactance to high frequencies, but high reactance to low frequencies, in series with the resistance (see Fig. 8).

In a typical case, resistances of the order of 1 000 ohms for short sprays, and as low as 300 ohms for the termination of long lines, were used. From formula (14) it is clear that even short-circuiting the end of a line will not make any difference to the d.c. sending-end resistance of a line, but obviously, if the condensers in series with the line termination resistances are not used, consumers at the end of long lines which are terminated with, say, 300 ohms, would suffer a severe loss of bass reproduction. This is said to reinforce the fact of the necessity for the

series condenser, which should have a value around $0.1 \mu\text{F}$.

It is perhaps worth while recording, in order to prove that these experiments and calculations have a practical as well as a theoretical significance, that, after a line had been "treated" in the way described, many consumers who took their service from it remarked upon the improvement in quality, although they had not been told

with line loading, and, with a given line loading, with frequency.

It is not difficult to design a transformer having good regulation at low frequencies, but a particular problem arises when supplying power to a wire-broadcasting network, because this may have a very low impedance at high frequencies $[\omega_s/(2\pi)]$.

We have seen that Z_{ns} , the sending-end impedance of

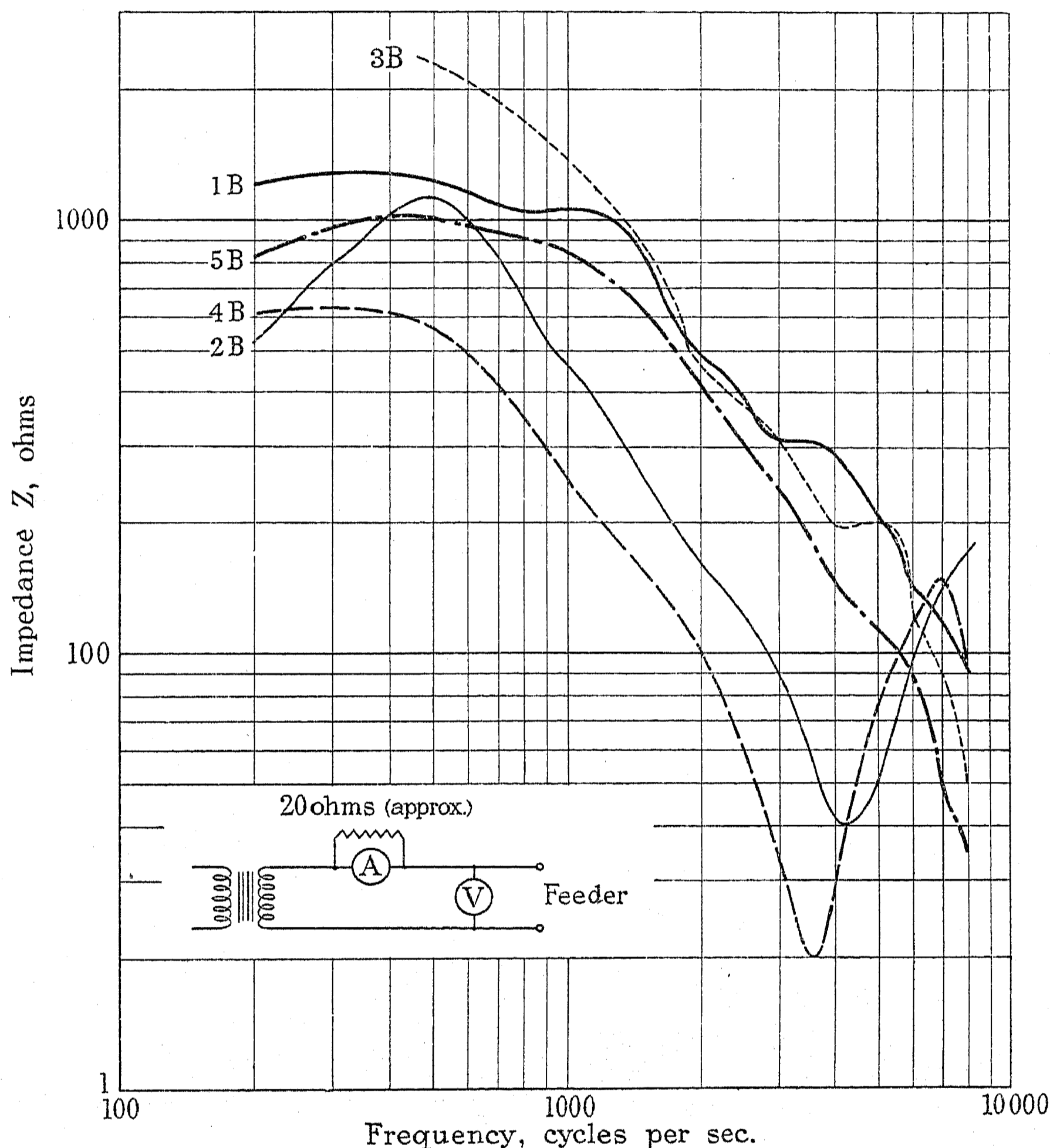


FIG. 6(c).—Characteristics of "B" feeders at 200–8 000 cycles per sec. Tests taken at Wolverhampton in June.

NOTES:—Feeders 1 and 2 run in twisted vulcanized-rubber wires for the greater part of the first $\frac{1}{2}$ mile.
No. 2 feeds an estate and has a good deal of lead-covered cable at the end.
No. 3 is mainly open wire for the first $\frac{1}{2}$ mile; at the end the voltage at 5 000 cycles per sec. was about 3 times that at the sending end.
No. 4 has a good deal of lead-covered cable, which is earthed throughout.

that any changes were being carried out. The loudspeakers used in this case were, furthermore, of a cheap type.

DESIGN OF OUTPUT TRANSFORMERS.

The transformer matching the amplifier valve output to the line has to give a sensibly constant output under all conditions of line loading.

The impedance of the line load at any frequency varies

the line at some high frequency, may be very low indeed, as low, in fact, as Z_{nb} , the impedance at low frequencies. It is obvious that the slightest leakage inductance will have a serious effect in cutting down the upper frequency output around and at frequencies $\omega_s/(2\pi)$. It is good practice, for example, to make the primary magnetizing current at 50 cycles per sec., say, one-tenth of the full-load current. This requires an inductance value, even for low-impedance valves, of the order of hundreds of

henrys. A 1 per cent leakage inductance at a frequency of, say, 5 000 cycles per sec. may cut down the output by 10 decibels or more!

It will thus be seen how important it is to sacrifice some performance at low frequencies in order to obtain even a passable performance at high frequencies.

R. E. H. Carpenter has suggested, and certain experiments appear in some measure to justify his contention, that the type of core shown in Fig. 7(a) will give a lower leakage inductance than the more conventional type in Fig. 7(b). It is obvious that the square core allows a closer association between windings and core and between

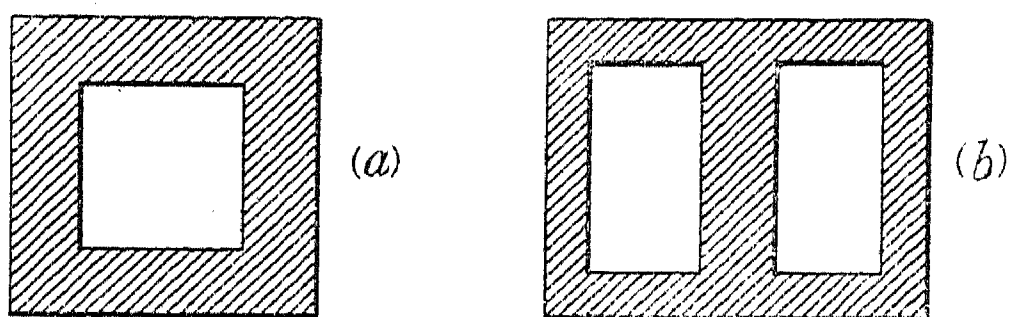


FIG. 7.—The core shown in (a) should allow a design of transformer having less leakage inductance than that shown in (b).

winding and winding than the so-called shell type [Fig. 7(b)].

Some measurements taken on a typical rediffusion transformer are as follows:—

Ratio	12/1
Valve impedance (optimum)	6 000 ohms
Secondary load	40 ohms
Leakage inductance measured in secondary by connecting capacitance in series and tuning to resonance	5 mH
Efficiency at 50 cycles per sec.	80 per cent
Loss at 5 000 cycles per sec. working into 40 ohms:—	
Theoretical	6 decibels
Measured	3 decibels
	{ discrepancy not understood

POWER REQUIREMENTS.

The term “loud-speaker power” is extremely ambiguous and even when defined is not directly related to the power required to be delivered from a rediffusion amplifier.

In the first place the performance of an amplifier is determined not by the power but by the volt-amperes it is required to supply to the load.

Secondly, the author has pointed out* that the analysis of the spectrum of typical programmes shows that the voltages applied to a loud-speaker reproducing typical programme material vary enormously with frequency.

Thirdly, the impedance of loud-speakers varies with frequency.

Fourthly, the loudness of reproduction required varies with audiences and the rooms in which such audiences listen.

Fifthly, in audio-frequency rediffusion the sending-

end impedance of the line is not determined by dividing the impedance of a typical loud-speaker by the number of speakers connected to a line. In fact, if the line loading factor given earlier in the paper is adhered to, then $Z_{nb} = Z_{ob}$ (very nearly), and it is apparent that the value of Z_{nb} will not be affected even though the end of the line is short-circuited or however long the line or however many loud-speakers energized, always provided that the spacing between consumers is of the order of 20 m in the first sections of the line.

Thus we wish to know:—

(1) The voltage at different frequencies across loud-speaker terminals required to give satisfactory strength of reproduction, assuming the reception of typical programmes.

(2) The feeder impedance at different, lower, audio frequencies.

(3) From (1) and (2) the maximum volt-ampere demands of the lines, assuming *any* loading equal to or greater than the maximum specified earlier in the paper.

To make point (3) clearer, it must be appreciated that an amplifier could energize, without its being overloaded, a line, say 10 miles long, feeding 5 000 consumers, because Z_{nb} cannot fall below a certain value (Z_{ob}) which is independent of the length of the line and only dependent upon R_1 (see Fig. 2). (Of course, consumers at the end of such lines would get a very poor service. They would be robbed of the lower and the top $[\omega_l/(2\pi)]$ frequencies, but they would still hear something which might be intelligible.)

A test made to determine point (1) above, by using a frequency-selective voltmeter, showed that the maximum peak voltage ever recorded across a loud-speaker giving satisfactory volume in a typical living-room was of the order of 100 volts at a frequency of 200 cycles per sec., and of the order of 70 peak volts at a frequency of 50 cycles per sec. The sending-end impedance of the line is of the order of 25 ohms (minimum) at 50 cycles, to 50 ohms at 200 cycles. Thus, the maximum r.m.s. volt-amperes required, whatever the line loading, i.e. however many loud-speakers are connected beyond a certain number, is about 100 volt-amperes (r.m.s.) per line. Four to six lines may terminate at one station.

Some calculate their power requirements on a basis of millivolt-amperes per loud-speaker. This is quite allowable where line impedance or resistance is negligible, but in ordinary overhead open-wire systems it may result in the installation of amplifiers of unnecessary power. The calculations above, for instance, show that if the loud-speaker has an impedance at 50 cycles of 3 000 ohms, then the millivolt-amperes demanded by it are of the order of 400. On this basis a line carrying 1 000 consumers might be reckoned to require 400 volt-amperes; but we see that 100 volt-amperes would suffice whatever the number of loud-speakers on the line.

It should also be noted that the modulation voltage at high audio frequencies is nearly negligible compared with that developed at low audio frequencies, and therefore, so far as power requirements go, there is no need to take precautions to supply extra power at frequencies $\omega_s/(2\pi)$ when series resonance takes place, even though the sending-end impedance may be very low.

Lastly, it is worth remarking that few engineers

* “Required Minimum Frequency Separation between Carrier Waves of Broadcast Stations,” *loc. cit.*

engaged upon designing and maintaining rediffusion systems will agree as to the necessity to use as much as 100 volt-amperes per line. Obviously the power requirements can be minimized almost indefinitely by arranging to "cut" the bass frequencies in some part of the amplifier preceding the output stage, or by allowing blasting, or by connecting resistance in series with the lines.

The author believes that the ideal of 100 volt-amperes per line is "uncommercial" because it does, of course, legislate for full reproduction at 50 cycles. It is worth while, however, to state the ideal and see how it must be modified. The author suggests that 50 volt-amperes per line having a d.c. sending-end resistance of 25 ohms (minimum) is a practical ideal.

Certain engineers favour the use of one amplifier per line; others think that all the lines distributing one programme can be brought to a common busbar to which one amplifier is connected. The latter practice, which is reminiscent of power-station engineering practice, is recommended where the wiring has been well done and where it is unlikely that earths, breaks, "marrys," and so forth will occur. If faults occur on one line and this line is in parallel with several others, then all lines will suffer because of the defects of one. Where there is a separate amplifier per line this trouble is eliminated. On the other hand it is probable that the amplifier cost, expressed as "cost per undistorted watt output," rises as the power output is less, there being certain constant costs involved whatever the power capabilities of the output stage.

CROSS-TALK.

It is difficult at all times to avoid cross-talk between lines carrying different programmes. Cross-talk could

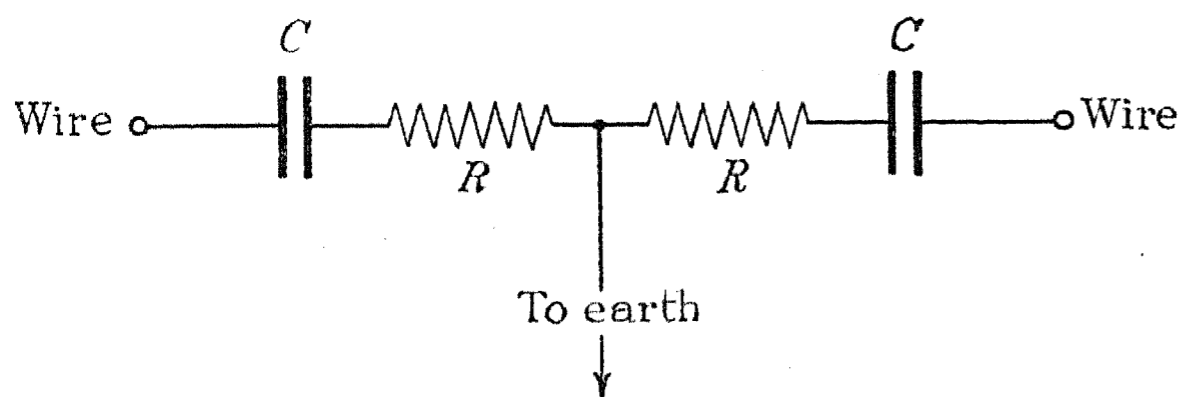


FIG. 8.—Suggested form of line termination and cross-talk eliminator. C should be of the order $0.1 \mu F$, and R will be greater the shorter the distance between the points where the device is connected to the lines. R varies between 1 000 and 200 ohms.

not take place if lines were perfectly balanced, i.e. if the currents and voltages were in exact phase opposition so that practically no external field was created. But the insulation may be different on different wires, and short-circuits to earth may occur. Lines may become short-circuited, wire to wire, creating very strong fields, when slight out-of-balance effects cause cross-talk.

It would appear to the author to be good practice, therefore, to anchor the electrical centre-point of a line to earth at frequent space intervals along the line and to make this, for high frequencies in any case, the determining impedance to earth (see Fig. 8). The arrangement shown in Fig. 8 has the double advantage of giving proper termination of lines and of anchoring the electrical centre-point firmly to earth.

THE AMPLIFIER.

A specification drawn up by the author for a rediffusion amplifier installation for a 4-feeder network and a 2-programme service is given hereunder and sufficiently describes the requirements of amplifier design without further comment:

General.—It is required to have a thermionic valve amplifier to convert a small power input to a large power output, the frequencies of the applied disturbances equalling those contained in the gamut of audible sound.

The equipment must be designed and constructed with the primary object of ensuring good quality of reproduction and reliability in operation.

Two amplifiers are required, one for one programme "A" and one for the other programme "B." The arrangement shall be such that the power available per programme shall be at least 200 watts of undistorted power as defined hereafter. This output will be derived from one so-called "generator," which might be more commonly described as an output stage of the amplifier. The equipment must be so designed that, by the addition of a new generator or new generators, the power output per programme may be increased 2, 3, 4, etc., times as 1, 2, or 3 generators are added to the basic equipment.

It is desirable, however, that the amplification of programmes "A" and "B" to a level sufficient to energize the input of the generators should be supplied by a unit which will suffice even though more generators are added.

The following specification applies to one generator and its associated amplifier necessary to energize that generator:—

	Volts	Resistance	Power at 200 cycles per sec.
Input	0.25	600 ohms	10^{-4} watt
Output	(min.) 35	(min.) 6 ohms	200 watts

Power amplification about 60 decibels.

Frequency Discrimination.—When the input, of pure sine-wave form, is varied in frequency between 30 and 10 000 cycles per sec., the maximum output power defined as above shall not vary more than 2 decibels between limits of frequency 50 to 8 000 cycles per sec., or more than 4 decibels between limits of frequency 30 to 10 000 per sec.

Distortion Limits.—When the input is of pure sine-wave form and when the amplifier is giving the required maximum amplification defined above, the voltage of the first, second, and third harmonic shall not be greater than 5 per cent of the voltage of the fundamental, whatever the frequency of the fundamental, provided the harmonic is in the audible frequency range.

Power Supply.—The power supply will be derived from alternating-current mains having a periodicity of 50 cycles per sec. ± 5 per cent. The voltage of the supply may lie between limits 190 and 260 volts inclusive, and suitable arrangements must be made so that the amplifier is quickly adaptable to any of these voltages. The voltage variation of the mains will be that commonly met with in Great Britain and, irrespective of the legal limits and in spite of this variation, the performance of the amplifier must always satisfy the requirements of this specification. Manual operation to compensate for mains voltage variation may be supplied.

The actual power taken from the mains for efficiently energizing two complete amplifier equipments, each having one generator unit, shall not exceed 6 kilowatts.

Output Transformer.—It is assumed that it will be necessary to supply an output transformer to work from the relatively high-impedance thermionic valve or valves of the power-output stage into the low-impedance line. The secondary of this transformer is to be supplied with tapplings so that the full power, with least distortion, can be fed into a non-inductive resistance of either 6 or 24 ohms.

There must be no appreciable drop in voltage between the output terminals of the equipment and the terminals connecting to the secondary of the output transformer when the equipment is delivering full power into the non-inductive load mentioned above.

The design of the output transformer must comply with the Post Office Regulations outlined in their "Summary of Conditions Governing the Establishment of Wireless Exchanges" dated January, 1932, relevant extracts from which are given hereunder.

"10. The following technical conditions must be met on the Distributing System.

"(a) Between the anode circuit of the output valve at any Exchange and the outgoing distributing wires from the Exchange a suitable step-down transformer, with an efficient screen between the primary and secondary windings, must be provided. The screen must be efficiently earthed.

"(b) The insulation between any winding of the transformer and screen must withstand the application for two minutes of an alternating voltage at a periodicity of 50 cycles per second of twice the value of the voltage to be applied to the anode of the output valve or valves. The insulation between any winding connected to the anode circuit of the output valve or valves and any winding connected to the distributing network must withstand for two minutes the application of an alternating voltage at a periodicity of 50 cycles per second of four times the value of the voltage applied to the anode of the output valve or valves.

"(c) Between the transformer and the anode current supply a suitable fuse must be inserted.

"(d) The screen referred to in clause (a) must be capable of carrying for 15 seconds at least three times the operating current of the fuse in the anode current supply circuit of the output valve or valves.

"(e) The lead providing the earth connection referred to in clause (a) must be capable of carrying five times the fusing current of the fuse referred to in clause (c). The earth lead must be joined to the earth connection of the anode current supply circuit."

Manual Variation of Amplification.—It shall be possible continuously and smoothly to vary the power amplification of the device from zero to maximum positive amplification by the adjustment of not more than two potential dividers, the position of the knobs of which should be indicated by a scale. The adjustment of one of these potential dividers shall provide an approximately linear relationship between "gain," measured in decibels, and angular movement of the rotating knob adjustment over a range of at least 35 decibels. The second potential divider is intended simply to adjust to a mean level

when the amplifier is installed, and need not vary the voltage output according to a logarithmic law. The adjustment of the potential dividers should not produce sudden variations of output audible in a loud-speaker, as typically used in rediffusion, connected across the output.

Monitoring.—It must be possible to monitor quickly, by headphones, the quality of reproduction before and after each successive stage of amplification, and the level of sound reproduced in the headphones must be substantially the same whatever stage is being tested, provided the overall amplification of the equipment is the same.

Meters.—It is not necessary to lay down exactly how many meters shall be used and in which circuits, but it is the object of the design to enable the unskilled attendant to check the performance of the apparatus by sight rather than by ear.

Construction.—The full equipment shall consist of three units, viz. one unit containing the "A" and "B" programme amplifiers up to the generator input, and two units as generator for "A" programme and generator for "B" programme. Each of these units must contain a separate power supply for the thermionic valves used so that any can be supplied separately. The units will be clearly labelled "A" and "B" respectively.

The construction should be such that it enables a skilled person quickly to inspect and clean the internal parts of the amplifier, which must, nevertheless, be reasonably protected from dust and shielded so that in working conditions no one may experience electric shock by being able to touch a "live" component. All components must be readily accessible for replacement and inspection. There must be no annoying noise, due typically to contactor tremble, etc., while the equipment is in operation.

The amplifier may form part of a shop-window display, and therefore superlative finish and brightness of external appearance are recommendations of the apparatus. "Finish" must be durable even if subjected to strong sunlight.

Heat Run.—The temperature of any component (excluding valves) shall not exceed the temperature of the surrounding air by more than 70 deg. F. after the equipment has been continuously delivering full power output during 5 hours.

Insulation Resistance.—The insulation resistance, when measured by means of a 500-volt Post Office type "megger," shall read infinity when tests are made as follows:—

- (1) Between any two conductors in cable forms when disconnected from any part of the amplifier equipment or associated apparatus.
- (2) Between any conductor and earth when disconnected as above.
- (3) Between any terminal and earth, excluding earthing terminals of transformers, etc.
- (4) Between any two conductors from the secondaries of the output transformers when disconnected from the transformer.
- (5) Between any conductor from the secondary of an output transformer and earth.

Valve Replacement.—The valve replacement cost (including rectifier valves, if used) shall not exceed £22 10s. per 1 000 hours' working. If, after service, this figure is exceeded it is expected that new valves will be supplied with the necessary adjustment of price to bring performance within the figure specified.

The purchasing company, upon the other hand, guarantee to keep "log sheets" showing the conditions of working, and these will be open at any time for inspection by the company supplying the amplifier or the valves.

Audio-Frequency Oscillator.—It is required to test the apparatus, and particularly to balance the push-pull circuits, by introducing an alternating e.m.f. of pure sine-wave form to the input terminals of the amplifier. The oscillator itself will be in a separate containing case and is therefore made the subject of another specification, but the power supply for the oscillator will be derived from suitable points in the equipment covered by this specification. It is desirable to provide means so that these connections can be quickly and correctly made and so that no inadvertent wrong connection can take place due to carelessness. Thus, if a plug-and-jack system, using more than one plug, is adopted, it should be so arranged that only the suitable jacks fit the correct plugs. Particularly, also, there should be no possibility that the monitoring telephone jack should fit the oscillator power-supply plugs.

Balancing of Power-Stage Output.—If class B amplification is used, in any degree, it is imperative to ensure that the performance of one-half of the push-pull circuit of the output stage shall be exactly similar to that of the other half. It is therefore preferable to match one output valve with the other, and all valves supplied for these equipments will be marked with a label showing the feed current for a given high-tension voltage and given steady negative grid-bias, which will be those used in working conditions without modulation. Nevertheless, this will not ensure exactly similar working characteristics for each valve, and therefore arrangements must be made to supply potential dividers arranged to vary the modulation input from the penultimate stage to the grids of either of the output valves independently. By means of these potential dividers adjustments can then be made, if a pure tone input is supplied to the amplifier input, to balance the valves in working conditions and thus eliminate any harmonic distortion due to non-matching of the two halves of the output push-pull circuit.

CONCLUSION.

There are many problems inherent in the maintenance of an audio-frequency rediffusion network, e.g. to keep the insulation in good condition, the circuits "through," and the lines free from short-circuits. This paper does not attempt to deal with these questions, since it was intended only to explore certain rather general problems inherent in giving good-quality service. It is not irrelevant, however, to point out that these and other practical problems find their solution in the use of either special buried cable networks (for audio-frequency wire broadcasting) or of modulated high-frequency currents superimposed on existing networks.

In both these cases the network is safe from damage

from the weather. (Not long ago a blizzard brought down several hundreds of chimneys in a certain town and destroyed a large part of an overhead audio-frequency rediffusion network.)

The number of programmes available is limited if overhead networks are used. Overhead networks are not sightly, although they could be made less obtrusive if wayleaves were more readily granted. Overhead networks supply a demand, but will disappear as newer and better methods of wire broadcasting are introduced. Since, however, it is better, if they are to be used, to use them properly rather than casually, the following conclusions are given in the hope that they may be of value to those who are technically responsible for designing and maintaining audio-frequency rediffusion services.

(1) The resistances and reactances involved in a line loaded by loud-speakers in the manner commonly met with in overhead-network audio-frequency rediffusion systems produce changes in power-level over the system, which changes vary with loading and with frequency. They also produce considerable variation of line sending-end impedance at different frequencies.

(2) In order that the loss of bass reproduction at and near the ends of lines remote from the sending end shall be minimized, a series resistance of the order of 2 000 ohms should be connected in series with the loud-speakers, which are preferably of the moving-coil type.

(3) To avoid a loss of bass reproduction greater than 6 decibels at a frequency of 50 cycles per sec. at and near the ends of lines remote from the sending end, the length of the line in kilometres multiplied by the number of consumers given service from that line should not exceed the number 600 if moving-iron speakers are used, or 1 200 if moving-coil speakers are used. Nevertheless, for practical working this number can be exceeded and factors as high as 1 000 for moving-iron and 2 000 for moving-coil speakers are tolerable, if not ideal.

(4) To avoid an exaggeration of high frequencies due to the resonances set up between the capacitance of the lead wiring and the inductance of open-wire lines, it is advisable to connect across the open ends of lines and sprays, resistances in series with condensers as shown in Fig. 8.

(5) The precautions mentioned in (2), (3), and (4) above, will tend to make the sending-end impedance of the line more constant than when they are not taken, but the output transformers of the amplifier must, nevertheless, be designed to have the least possible leakage inductance.

(6) The amplifier power should be calculated for ideal conditions on a basis of 100 volt-amperes per line fed from the amplifier, provided always that the networks used are similar to those illustrated in Figs. 1 and 2 of the paper; but a reduction of this figure to 50 volt-amperes is allowable. If buried cable with lower-resistance conductors than those used for overhead networks is installed, power should be calculated on the basis of 400 millivolt-amperes per loud-speaker, or, allowing for the usual diversity factor, say 300 millivolt-amperes per loud-speaker.

In practice, amplifiers feed as many as four lines and must supply, therefore, for a "practical" ideal 200 volt-amperes working into an impedance of the order of 6 ohms (minimum).

ACKNOWLEDGMENTS.

The author wishes to thank the Managing Director of the Nottingham Rediffusion Services, Ltd., for his permission to conduct the experiments described in the paper, and to Mr. W. T. Sanderson, the chief engineer of that company, for his help in carrying out the experiments.

The author is particularly grateful to Mr. A. L. Bauling, who set up and ran the first audio-frequency rediffusion system in the world in Holland, for his help and his kindness in allowing the author to inspect many of the rediffusion systems now in operation in Holland under Mr. Bauling's direction.

DISCUSSION BEFORE THE WIRELESS SECTION, 11TH APRIL, 1934.

Mr. N. Ashbridge: Wire broadcasting has the great disadvantage that it cannot serve those districts which in some cases radio broadcasting also cannot reach, namely the scattered and very often mountainous districts. This, I suppose, would also apply to wire broadcasting over electric light wires, because there is usually no electric light in such districts, and where there is the nature of the lines would probably present very grave problems. On the other hand, where these systems can be applied with financial success—that is to say, in cities and towns—they are not necessarily redundant, because they can get over the serious difficulty of the non-preventable type of industrial interference. Unfortunately, however, the places where rediffusion exchanges have been installed are in many cases exactly those where the radio service is about as good as it could be.

With regard to distortion, before reading the paper I had not realized the possibilities of the listener getting far worse reproduction from wire broadcasting than he is likely to obtain from a comparatively cheap radio receiver.

The author does not mention the means of collecting the programme. Many rediffusion exchanges radiate foreign programmes, and I should like to know what steps are taken in these circumstances to prevent fading and interference. I am aware that the receiving point is outside the city and a favourable site is chosen, but, for example, are Bellini-Tosi aërials used? I should like to ask whether interference with wire broadcasting is experienced from tramways, when open wiring is used.

Do the rediffusion exchanges supply all the loud-speakers connected to the system? If not, conditions might become chaotic, because some enterprising electrical firm might produce a loud-speaker which absorbed more than its share of the energy.

Finally, I should like to refer to the author's use of the word "disturbance." Cannot we find a better word than this to convey the idea of music currents and speech currents?

Mr. P. Adorjan: It may appear from the paper that each feeder has a characteristic sending-end impedance/frequency curve (I am referring to Figs. 6*b* and 6*c*), and although the author mentions that a variation of the sending-end impedance may take place with the variation of load he does not make it clear that the shape of the curve varies considerably with the load. Actual measurements show that the same feeder has different sending-end impedance/frequency curves on light, medium, and heavy load. The shape of the curve for light load will approach that of Fig. 6*c*; on medium load it will approach that of Fig. 6*b*; while on heavy load the sending-end impedance increases rapidly with the

lower frequencies and reaches a value at which it remains practically constant up to 5 000 cycles per sec. or more, falling off at the higher frequencies. It may be purely accidental that in the case of Fig. 6 (*b*) the minimum dips of the impedance curves coincide with the maxima of the level curves.

The author suggests that a line loading-factor given by $nl = 0.85R_s/k$ be adopted. This, however, is not the most economical working condition in the case of large systems where several thousand subscribers have to be supplied from the same station. The largest part of the capital cost in a rediffusion system is the cost of the feeder network, and this can be minimized by connecting as many subscribers to a feeder as possible. In arriving at the formula for nl the author starts with the assumption that V_n must never be less than $\frac{1}{2}V_0$ at 50 cycles per sec., but it is obvious that as far as subscriber n is concerned it is of no importance how his line voltage at 50 cycles per sec. compares with the sending voltage and/or with the 50-cycle voltage received by subscriber r . All that matters is that subscriber r and subscriber n should receive line voltages in similar proportion to the sending voltage at all frequencies. If we allow for subscriber n , which of course is the worst case, a frequency discrimination of 4 decibels between 50 and 7 000 cycles per sec., which is better than the frequency response of the average wireless receiver, we have the condition that $V_{np}/V_{nb} \leq 1.58$. This condition has been fulfilled even on a very heavily loaded line. The overall level is governed by V_{nb} , which is equal to $V_0/\cosh n\theta$, and V_{np} can be reduced to $1.58V_{nb}$ by using sufficiently low values of terminating resistances. The sending level is so adjusted that V_n gives sufficient acoustic level in the reproducing loud-speaker. It may be argued that this will result in an excessive level at o and r , but this can be overcome by increasing the R_s values of the earlier loud-speakers.

In practice it has been found that it is unnecessary to supply different types of loud-speakers to subscribers along the feeders, but a volume control should be included in each loud-speaker, and this in effect increases R_s . The increase in R_s results in an increase of $1/\cosh n\theta$, and the large use of these volume controls near the station explains why, on the lines where the load factor is very much higher than the author's figures, the attenuation at 50 cycles per sec. is less than 6 decibels.

When dealing with the general aspects of rediffusion one must at least mention the considerable developments which have been made in high-voltage rediffusion, especially by Standard Radio Relay Services, Ltd. A form of rediffusion grid system which has been developed by Mr. G. M. Jenkins, chief engineer of this concern, and myself, is now working in several towns. In one particular case, a substation supplying 1 400 subscribers,

which previously employed local amplifiers, is supplied at high voltage by means of high-level links from another station about 2 miles away, the apparatus at the sub-station consisting only of transformers and distributing, switching, and testing gear. This method has several advantages, and in the case of densely populated areas results in a reduction of running costs.

Over 5 miles of specially designed underground cable is being laid at present for the completion of the Isle of Thanet rediffusion grid system. This represents an addition to the sections already operating. With the type of wire used, a high margin of safety is provided as regards insulation, whilst the inter-line capacitance is still kept low. This, however, does not result in an uneconomic increase in cost.

In connection with the amplifier specification, the following points may be of interest. The amplifier for which the specification was drawn up delivers an audio-frequency power of 300 watts with 5 per cent total voltage harmonics, and 450 watts with 10 per cent total voltage harmonics; the valve cost has been considerably reduced from the value stated in the specification. In the amplifier described, H.T. voltages of over 1 000 volts are required, and therefore the specification quoted is not adequate. It does not cover the special Post Office requirements for these voltages and the additional protective devices which must be used.

If class B amplification is used in connection with large output valves, and corresponding large changes in the anode current take place, then, although the maximum plate voltages are only of the order of 1 500 volts, instantaneous peak voltages of over 8 000 volts may develop when a large input is suddenly applied. Such an input may be due to atmospherics picked up by the receiver, or even directly by the lines joining the remotely-situated receiver to the amplifier. The voltage will be a function of dI/dt , where I is the anode current in the output stage. Spark-gaps which had been previously set to 8 000 volts broke down under these conditions, and it was necessary to install special input-limiting devices in an early stage to eliminate this trouble.

Another point which has not been dealt with in the specification is the method of switching on the H.T. supply. For large class B amplifiers, the H.T. supply has to be obtained from mercury-vapour rectifier valves in order to get good voltage regulation, and a smoothing circuit containing several large condensers must be used to eliminate mains hum. It is found, however, that when the H.T. is applied in the ordinary manner, momentary charging currents several hundreds per cent higher than the ordinary full-load current are taken. It is therefore necessary to employ a device which will ensure that the H.T. currents will be switched on gradually, the applied voltage being increased to its final value in two or more steps. Otherwise the life of the rectifier valves will be shortened.

Since this amplifier was evolved a smaller amplifier has been designed by Standard Radio Relay Services, Ltd., giving 85 watts with 5 per cent total voltage harmonics and 105 watts with 10 per cent total voltage harmonics. The initial cost of the second amplifier per audio-frequency watt output, and the maintenance cost per audio-frequency watt-hour, are lower than the

corresponding costs for the amplifier dealt with in the specification given in the paper.

The author apparently makes no mention of radio receivers, on which so much depends in the rediffusion field. In practice it is found that three different types of receivers are required. For local reception, when the radio transmitter is within 50 miles of the receiving station, diode receivers can with advantage be used. A high-frequency pentode followed by a diode may be employed for more distant stations which can be received without interference; such a receiver embodies iron-cored coils. Superheterodyne receivers should be used for the reception of stations which are difficult to receive without interference. Some form of tone correction, and also automatic gain control, must be included in the last two receivers. Special superheterodyne receivers are necessary for occasional transatlantic short-wave relays. Directional aerials have to be used where interference from shipping or other sources is very bad.

The receiver switching must be so arranged that receivers can be interchanged during transmission without interruption to the service. For example, if a programme is being received from the London National station and this is being interfered with, another receiver which is tuned to the West National, sending out the same programme, may be faded in and the first receiver faded out.

Finally, it may be of interest to state that the first audio-frequency rediffusion system, which is still in operation, was started in 1896 in Budapest. The method employed is very different from that of the so-called Electrophone. The company erected its own feeder network and studios, and its transmissions included, in addition to the news bulletin and concerts from the studios, frequent relays from the opera house and the theatres. The sending level, of course, was very low and headphones were used at the subscribers' premises. Since the advent of the thermionic valve, small amplifiers and loud-speakers have been available for subscribers. These, however, never attained great popularity, and this is attributable to the fact that the principal attraction of rediffusion lies in the subscriber being able to obtain high-class reproduction at good volume without the trouble entailed by the use of valves.

Mr. R. E. H. Carpenter: The author refers to my advocacy of the use in audio-frequency transformers of core-type stampings in preference to those of the shell type, and it may perhaps be of interest to add to what he says. In the first place, it is of course assumed that the core shown in (a), Fig. 7, has the windings equally distributed between two of the parallel limbs, while that shown in (b) has the windings on the central limb only. In the core type one has, other things being equal, twice the axial winding length. Consequently twice the number of pancaked sections of a specified thickness can be employed, and the outside diameter of these sections is considerably reduced; hence the coupling is tighter and the copper losses are considerably less. Moreover, the increase in the percentage coupling is greater than would be expected from a consideration of the increase in the number of sections alone, since the mean turn for these sections of smaller diameter is nearer to the core material. The importance of this consideration in giving tighter

coupling is clearly greater, the greater the permeability of the core material employed. The core type of transformer has a further important advantage in that it is less liable to be disturbed by induction from external magnetic fields, since the windings on opposite limbs are of opposite sense; and for the same reason it is less likely to cause induction troubles in other apparatus. In brief, the core type gives tighter coupling, low copper losses, and an approach to astaticism. In practice it is quite easy to get about half the stray inductance on the core type as compared with the shell type.

Mr. A. C. Timmis: The author departs from a well-established tradition of the telephone engineer when he uses θ to represent the attenuation constant.* This symbol is universally employed for the propagation constant. Thus $\theta = \alpha + j\beta$, where α is the attenuation. On page 342 the author says that in designing a transformer having good regulation at low frequencies it is desirable to make the primary magnetizing current at 50 cycles per sec. one-tenth of the full-load current. This is very extravagant, and strongly favours the low frequencies as compared with the high. In transformers for audio-frequency and carrier-frequency work we generally take a ratio of about one-quarter to one-half at the lowest important frequency. The losses caused by the shunting effect of the inductance of the transformer are not generally serious. A ratio of one-quarter to one-half corresponds to a loss of only a decibel or so.

I do not think the leakage circuit in Fig. 8 would be satisfactory. It really amounts to connecting a condenser and a resistance from each wire to earth. That, of course, would have the effect of swamping the variable factor, leakance, but one would expect to lose almost as much in attenuation, through the shunting effect, as is gained in regard to cross-talk; so that the final signal/noise ratio would be about the same as that obtained when no such shunting arrangement is adopted.

The idea of carrier-frequency distribution is very attractive. The suggestion was made a year or two ago that the Post Office should distribute programmes by means of certain carrier frequencies—say, between 30 and 100 kilocycles per sec.—impressed on a telephone cable at the exchange, the programme being picked up by connecting a suitable receiving set to the telephone line at the subscriber's house and tuning to the programme desired. We made a few experiments in this direction using a power of only about 0.2 watt put on at the exchange, and a cable about $1\frac{1}{2}$ miles long. We found that it was necessary to use a 3-valve set in order to pick up the programme at reasonable loud-speaker strength. There was no particular difficulty, except that the telephone signalling apparatus, automatic selectors, relays, etc., seemed to produce an extraordinary amount of radio-frequency interference. The idea was dropped because it was generally felt that if a subscriber had to use a 3-valve wireless set he would not like to be limited to three or four programmes, but would want to search the ether like other listeners.

Mr. W. G. Radley: There are two main methods on which a wire broadcasting system may be based, namely audio-frequency and carrier-frequency distribution. With carrier-frequency distribution the currents in the net-

work have frequencies above the audio range, and so are not likely to cause interference to the normal telephone service. The remarks which I have to make refer more to the possibilities and potentialities of the audio-frequency system as a source of telephone interference. Here we have a system which can be described as a power system. It is incidental that no low-frequency 50-cycle component is present; audio-frequency currents are present at a very much higher level than they would normally be in a power system, even with a very distorted wave-form. That the interference from such a system consists of a series of frequencies which combine to give music or speech is not important, because the interference is likely to cause as great a loss in articulation as if it were due to harmonics in a power system, and an equal amount of annoyance to the telephone user. The disturbance is reduced to a minimum when the currents in the two wires forming a line are exactly equal and opposite in phase. The necessary precautions are that the insulation resistances of the two wires should be maintained high and as nearly as possible equal, and, most important of all, that there should be no earth connection to the distribution system, either intentional or accidental. So far the companies operating wire broadcasting systems in this country are to be congratulated, because, with well over 100 000 consumers connected, comparatively few cases of interference to the telephone system have been reported. When they have, the trouble has usually been traced to an earth on the distribution system, and has been removed fairly quickly. It is in order to minimize the effect of a second or accidental earth that it is specified that no deliberate earth connection shall be made to the system, even though that connection is made at a neutral point, such as the mid-point of the output-transformer winding.

The paper deals mainly with the effect of the network on reproduction; I should like to ask the author whether it is not possible to give some sort of reproduction not only with an imperfectly designed network but even with a distinct fault on the network.

There are not many cases in this country where distribution actually takes place over Post Office telephone lines. In cases where they are used to connect a central station with a sub-amplifying station, it is recommended that the voltage output to the telephone circuit should lie between the limits of 1.4 and 0.3 volts. This is to prevent overhearing between the circuits, both to and from the broadcasting circuit.

As the author points out, it is quite possible for blizzards to bring down a large part of the overhead system. Now this system is connected to the output circuit of an amplifier, in which it is normal to have quite high voltages. In order to prevent accidental contact with these voltages the regulations given on page 344 are in force. The principle behind the regulations is that there shall be no physical connection whatsoever between the distribution system and the high-voltage circuit. Both these troubles would disappear if in place of the open-wire system a cable system were adopted.

Dr. L. E. C. Hughes: I should like to refer to the author's use of the word "level," to which communication engineers have hitherto attached a precise meaning.

* This has been altered for the *Journal* to read "transfer constant."

The transmission level at any point in a system is the power obtained in a matched load; that is, when the circuit is terminated in its impedance level. It is an actual power expressed in decibels relative to an arbitrary power level, e.g. 1 milliwatt. If the level is taken as depending on the square of the voltage on the line, regardless of the impedance to which it is applied, this leads to the absurd result that the level at the end of the line can be greater than the level elsewhere. I suggest that the author should use the term "tapped level" to distinguish it from the true transmission level, which represents, at any point, substantially the power which is passed on and not used, rather than the power which is abstracted by a tapped load.

In my experience of relay systems, a soundly engineered plant can give a superior performance (for its overall cost) to that obtained from a cheap radio receiver. In some systems, switching off a loud-speaker brings in an equivalent impedance, so that the total loading and tapped level is constant. If the zero-frequency loop resistance differs in the two cases, the number of subscribers listening is measured by the difference in a direct leak-current through the network. Such an indication shows how many subscribers are listening at a given instant, but in my estimation and experience does not afford a means of estimating the relative popularity of programme material with attentive listeners.

It is an acoustic fact that one can tolerate most kinds of music whether one is interested or not; on the other hand, speech in which one is not interested cannot be tolerated. The theory of toleration therefore indicates that the switching-over from speech to music by subscribers, which is commonly observed by relay engineers, is not safe evidence that talks are relatively unpopular, since it is also a common experience that the majority of listeners use the broadcast service as a pleasant background of noise to cover up more distracting noises; for much of the time, the programme has no direct significance for them. The relay service-man is, however, in a vital position to obtain the views of listeners on material which is significant to them, and ascertaining at first hand the average response of a certain section of the public to the broadcast service.

Mr. F. E. Wallcroft: I should like to call the attention of the author to the fact that the Post Office regulations which he quotes in the paper have been modified slightly since 1932, chiefly because of the developments which have taken place in the wire broadcasting art. With regard first of all to Regulation 10(a), the requirement that the screen must be efficiently earthed was framed at the time when it was assumed that there would always be an earth on the anode-current supply unit, and the reason for putting in such a condition was to ensure that the fuse in the anode-current circuit would blow if contact occurred between the screen and the winding. It was afterwards considered much better to specify that the screen should be connected to the negative of the anode-current supply, or, in the case of a 3-wire d.c. system, to the neutral. As regards Regulation 10(c), the expression "suitable fuse" has now been replaced by the words "1-ampere fuse." Turning to Regulation 10(d), whereas the current-carrying capacity of the screen was previously referred to in terms of the

operating current of the fuse, it has now been fixed at not less than 3 amperes. Also in Regulation 10(e) the lead required is now specified as not less in size than 1/036 in. copper, instead of in terms of the fusing current of the fuse. A further condition, to which Mr. Adorjan has referred, has been laid down in connection with apparatus using anode voltages of a high order. When schemes were put forward suggesting the use of voltages as high as 2 500 volts for the anode in the output valve, it was felt to be necessary to look more closely into the design of the output transformer in such cases. A line-discharging device has been specified on each of the lines leaving the output transformer or transformers, and this device must have a low impedance when discharging; otherwise it might discharge and yet not blow the fuse in the anode circuit.

Mr. F. Murphy: An essential ingredient of entertainment is the power of choice. It is not that people really want to listen to distant broadcasting stations: in spite of what they say, I think the majority of people in this country for 99 per cent of the time listen to the local station, though they like to pretend that the reverse is true. If, however, they were prohibited from listening to any but the local broadcasting station they would immediately be up in arms, because they would have been denied the power of choice. It is well worth considering, whether ultimately line broadcasting can be developed in such a way as to give the power of choice. Even if in the future a more extended choice is given than is possible at the present moment, with wire broadcasting the power of choice will always be more limited than in the case of broadcasting through the ether, for the simple reason that with line broadcasting it is essential at some central point to choose that one will pick up x stations and no more, and that x stations may not include the one for which I have a fancy at the moment. This point requires serious study. It seems to correspond to my experience of the use of relay services, namely that they are commonly used by the poorer class of customer, who, after he has had 12 months' experience of broadcasting via a relay system, buys a good wireless set.

Dr. E. W. Smith: With regard to branch feeders to consumers, cable manufacturers frequently receive inquiries from broadcast relay services which contain definite requirements as to capacitance, resistance, and insulation, but are extremely indefinite as to the cross-talk requirement. Would it be possible to suggest some cross-talk specification which could be conformed to satisfactorily? This point does not merit serious consideration when the line is as short as is generally the case, but if a general change from open wiring to cable wiring occurs this question will become of much greater importance. In specifying the cross-talk it is necessary to mention the type of termination, and it is also convenient to specify one particular frequency at which cross-talk should be tested. I suggest that the cross-talk of a consumer's branch feeder should not exceed 80 decibels with a termination of 500 ohms, and I should be glad to know what the author thinks of this suggestion. Has he any experience of the quad feeder cable as compared with the double-twin type? The cross-talk on the ordinary quad cable can be made very small, this being

the usual type of cable for underground and submarine telephone work. There seems to be no reason why superimposed working should not be carried out successfully on this type of cable. I presume the failure mentioned in the paper is due to the open-wire line; I do not think it would occur with a satisfactorily balanced cable.

With regard to the lead covering of consumers' branch lines, it may be mentioned that lines are giving satisfactory service in which each wire is insulated with a thermoplastic material similar to that used in submarine cables. Two or more pairs, screened in the usual way, are enclosed in a damp-resisting covering of the same material. This has the advantage over lead of greatly reduced weight.

Mr. E. S. Ritter: I should like to suggest the possibility, instead of running a pair of wires from the central point and then putting a termination on it to reduce reflection, of having a ring main running round at a certain radius from the central point and connecting it with feeders to the central point; or, as a possible alternative, running a pair of wires round a district and bringing them back again to the central point, thus avoiding having a pair of wires with an open-circuited termination. The problem is similar to that met with in electric power distribution, except that all frequencies in the audible range are required to be received at approximately the same level.

I notice that in the paper the author gives the inductance of the open wire but neglects its capacitance and leakance. Is this justifiable?

Mr. A. Cross (*communicated*): It is unfortunate for the technical development of audio-frequency wire broadcasting that information such as is contained in the paper could not have been made public at a much earlier date, for relay companies have lately sprung up like mushrooms and very few of these concerns have had the advantage of the author's guidance in the matter of the basic technique.

As a result, in many cases the rediffusion company has merely purchased an amplifier, erected some sort of network, connected the two together, and hoped for the best. It is to these companies that the conclusions embodied in the author's paper should be of particular value.

In the practical operation of audio-frequency rediffusion systems it has been customary to divide a town into areas, governed usually by geographical conditions, and in each area to set up a separate amplifying station fed from the remote receiving station by landline. When any network in such a system has become fully loaded, new amplifying stations have been set up to feed a part of the loaded network, thus allowing for further development.

This involves the rediffusion company in an increased annual expenditure for maintenance as the system grows, and it has been suggested that the problem might be overcome in a particular area of, say 30 square miles, by the erection of a number of unloaded feeder links to the various heavily loaded districts from a central amplifying station; the sending level being raised as high as possible consistent with the limitations of safety and possible interference with other services as mentioned in the paper. Step-down transformers

would be used at the ends of these links to feed loaded networks of the type dealt with in the paper. A practical scheme which has been put forward provides for a sending level of 70 volts (r.m.s.), the ordinary distributing level for the network being 35 volts (r.m.s.).

I should be interested to know whether the author considers that such a system would be of much practical use in the matter of relieving the load, and approximately the number of subscribers that he thinks might be fed in this way. It would seem from the paper that the adoption of such a scheme would entail a considerable increase of transmitted power, and frequency distortion would appear to be aggravated at the condition where series resonance obtains.

Mr. E. K. Sandeman (*communicated*): The paper represents the author's contribution to a new technique which, if comparatively simple, is likely to assume considerable importance, as will be realized when it is appreciated that there are already between 150 and 200 rediffusion companies operating in England alone. Rediffusion systems are also in operation all over the Continent, notably in Holland, Switzerland, and Belgium.

No mention has been made of that type of service in which programmes are relayed over telephone wires; this is sometimes called a "teleprogramme" service. A teleprogramme system has been operated in the Hague for some considerable time. Such a system now extends over the whole of Switzerland, and in April, 1932, there were 40 centres linked up by programmes transmitted over the main toll cable system. The studio at Lugano, when first installed, for a period of 9 months transmitted programmes solely for the benefit of rediffusion listeners.

A paper on diffusion over power mains at carrier frequencies would have interested me personally much more than a paper on audio-frequency rediffusion, and I should like to have seen figures comparing the economics of audio-frequency and carrier-frequency systems. One of the most important questions in designing a rediffusion system is the securing of a proper economic balance between the first cost and the annual charges on the amplifier system and network. This certainly appears to deserve careful attention in any future papers that appear on the subject.

No details are given of the very stringent requirements of a suitable radio receiver for rediffusion working, or of the circuits of such receivers, while no mention is made of any devices for visual indication of volume transmitted to the lines or for showing approximately the number of subscribers listening in at any given time.

Some mention might have been made of the fact that a rediffusion system should ideally be designed like a power network, with high-voltage feeders carrying power to subsidiary distribution centres. It is seldom that this ideal can be systematically realized in practice, but high-voltage feeders have been used both in England and on the Continent with a considerable degree of success.

Anyone who uses hyperbolic functions always commands my respect; personally I have always found them quite useless, because the only existing tables of complex functions are so incomplete and the methods of interpretation so cumbersome. The author's ingenuity in

simplifying the quantities concerned is admirable, but all problems do not lend themselves to such simplification. If it is not out of place here I should like to register a plea that some plan might be organized, possibly among a number of colleges, for the expansion of Kennelly's tables to fill up this gap.

I should like to know what advantage the author's method of earthing the middle point of the system has over the old expedient of earthing the mid-point of the line winding of the output transformer. I should have thought that if it is found necessary to earth the circuit at other points a choke coil bridged across the circuit and earthed at its mid-point would be preferable. Condensers can be added in series if required, to enable loop-resistance measurements to be made.

In conjunction with Mr. P. L. Tabois and Mr. P. R. Thomas I was responsible for the design of an amplifier to meet the requirements set out in the paper, and I found them to be entirely practical. A description of the amplifier in question is about to appear in the *Wireless Engineer*. An unexpected trouble which we encountered was the effect of high audio frequencies due to atmospheric effects caused by thunderstorms, which had the effect of breaking down the insulation of meters and blowing fuses until suitable audio-frequency voltage-limiting means were introduced. Before this, sparks $\frac{1}{4}$ in. long occurred in the anode circuit of the last stage.

Mr. P. P. Eckersley (*in reply*): I cannot agree with Mr. Ashbridge's statement that it is "a great disadvantage" of wire broadcasting that it cannot reach "the scattered and very often mountainous districts." It is hardly its function to do so. Radio broadcasting can best serve rural areas, and wire broadcasting urban areas. The use of a few (preferably long-wave) very high-power stations, suitably placed, would give a good service to all rural areas, leaving the towns to be served by a multi-programme rediffusion or wire broadcasting system.

The fact, mentioned by Mr. Ashbridge, that wire broadcasting systems have been highly successful in towns and cities where the field from a (local) broadcasting station is strong, perhaps indicates that the rediffusion service appeals on account of its reliability and cheapness, and also, perhaps, because it enables the subscriber to get a clear reception of distant stations which are neither drowned by the local station nor subject to the types of interference experienced in ordinary wireless reception in urban areas.

If the art and practice of wire broadcasting is to be properly applied it will be unnecessary to place wireless broadcasting stations in or near the centres of gravity of the densest populations.

Mr. Ashbridge and others have referred to the absence of any reference in the paper to the receiver which is used in rediffusion technique to pick up programmes suitable for relaying to consumers. This wireless receiver is, however, a redundant piece of apparatus in a properly conceived wire broadcasting system; there is no technical need to interpose a wireless link between microphone and consumer.

In some cases, where a rediffusion system exists in a town or city where there is also a local wireless broadcasting station, the "receiver" for the rediffusion

service is located immediately under the transmitting aerial and consists of an aperiodic input system and a diode rectifier the output from which is connected to a landline joining receiver and rediffusion amplifier.

Mr. Adorjan lays down certain rules for the design and construction of the wireless receivers essential to rediffusion, but the rules do not appear to have any foundation other than the fact that a certain company obeys them. It is obviously advisable to use simple types of receivers when the field of the station is strong, and necessary to have more selective and sensitive types if the field is weak.

Certain speakers have, with more or less justice, criticized the terminology used in the paper. It is inevitable and acceptable that such criticism should be forthcoming, seeing that the subject is new. Mr. Ashbridge asks for a better word than "disturbance" to describe the modulated currents conveying the programmes to be rediffused. One would welcome alternative suggestions, but, for instance, "energy" is as inaccurate as many other terms which have been proposed.

I wish to apologize that, in the original text, the term "attenuation constant" was used where obviously "transfer constant" was implied. This has been corrected and I am grateful to Mr. Timmis for pointing out the error.

Dr. Hughes criticizes the way the term "level" has been used in the paper, and points out that one interpretation of the curves might imply that the conservation-of-energy principle had been disproved in rediffusion systems. On the other hand, the word "level" was consciously used and the ordinates of the certain curves were purposely labelled in decibels. This action appears justifiable because the analysis was concerned with distortions in reproduced sound caused by the interactions of the network and the loud-speaker constants. The rising voltages across the loud-speakers over a certain band of frequencies will result in an increase in the level of the reproduction of those frequencies, and this fact is best expressed in terms of decibels. But perhaps these arguments are not acceptable to those who define level in a purely electrical sense.

I am in most emphatic agreement with Mr. Sandeman's dislike of hyperbolic functions. It is, however, interesting to notice that, provided networks are terminated in their image impedance, it is possible to treat the problem according to the much simpler filter theory involving only impedances, and for the most part without serious trouble with j . It is hoped that there are other and more solid recommendations for the use of the resistance termination of Fig. 8, but certainly the elimination of hyperbolic functions is one of them!

Turning now to questions concerned with the apparatus of rediffusion, it is interesting to be able to give further confirmation of Mr. Carpenter's contention that it is possible to get closer coupling between transformer windings with core-type than with shell-type stampings. In certain work, lately carried out in co-operation with Mr. Carpenter, I have been shown that currents of relatively very high frequencies indeed can be efficiently transformed to different impedance levels without serious loss due to leakage inductance, provided core-shaped

stampings (of suitable material and thickness) are used.

Mr. Timmis rightly disagrees with a specification which limits magnetizing current, in an audio-frequency transformer, at 50 periods per second to one-tenth full-load current, always assuming that the transformer has to work into a typical rediffusion network exhibiting large and uncorrected impedance deviations, particularly when these take the form of a lowered impedance at high audio frequencies. But my experience indicates that one can build extremely good transformers on the basis of such a specification, provided the load lightens as the frequency increases. This takes place when one, or a very few, nearby loud-speakers have to be energized. For instance, a transformer suitable for public address systems, where there are no series resonance effects in the loud-speaker leads, could well be designed on the basis of the specification given. On the other hand, I agree with Mr. Timmis that in certain other cases the specification may be unduly extravagant. The point made in the paper was that for audio-frequency rediffusion the specification was not only extravagant but definitely unsuitable.

The amplifier specification given in the paper was prepared in 1932 when I was actively engaged in work in connection with the detailed technique of audio-frequency rediffusion. I have since been engaged upon the development of carrier-frequency rediffusion technique and have therefore lost intimate touch with the latest details of the regulations. I am therefore grateful to Mr. Wallcroft and others for pointing out that certain changes have since been made in the Post Office regulations concerning amplifiers, and for listing them for the benefit of technicians actively interested in this subject.

Mr. Smith raises important questions in relation to cross-talk. His suggestions should be welcomed and discussed by technicians actively engaged in rediffusion development. It is obvious that one of the chief problems confronting the network designer lies in the prevention of cross-talk, which at times assumes serious proportions. Certainly, also, any mismatching at junctions of different types of cable and feeder would create specialized problems. It was hoped that cross-talk might be minimized by the connection shown in Fig. 8.

The paper was of limited scope. Its purpose, as Mr. Cross has pointed out in his communication, was to lay down certain guiding principles for engineers, which principles are based upon a quantitative appreciation of the factors involved. Not many have discussed this aspect of the paper, and none has brought evidence which convinces me of the necessity to change the conclusions arrived at. Mr. Adorjan suggests some form of "grading" whereby R_s , the loud-speaker series resistance, is increased near the station, and says that such a scheme might alter the load factor recommended. Obviously, such a scheme is not desirable because, loud-speaker impedance varying with frequency, different values of R_s will give different kinds of response for the same type of loud-speaker. To use, as is apparently suggested, a volume control which is a variable series resistance, acts in precisely the wrong way, making bass weak at weak amplitudes.

Loading affects the frequency-response curve and impedance/frequency relationship of the network, and Mr. Adorjan confirms that this happens in practice without apparently having recognized that it is implicit in the algebra, and stated in the text, of the paper that this will occur. Quite obviously, however, the whole analysis of network performance has not been appreciated if it is considered a coincidence that, in Fig. 6(b), Curve I_R dips approximately at the same frequency as the Curve I_V of the same figure achieves its maximum. If the voltages across one of the reactances in a series resonant circuit and the input impedance of that circuit are measured simultaneously, it will be an error of observation if the maximum of one does not coincide with the minimum of the other.

The prevention of non-uniform effects with different frequencies of applied disturbance might be obtained, as Mr. Ritter suggests, by the use of ring mains, but it is doubtful if they would be eliminated. With a ring-main connection one would expect nodes and antinodes of potential at points remote from the station.

I suggest that it is justifiable to neglect the capacitance of the open-wire lines in comparison with the large bunched capacitance in the subscriber's down-lead connection. Moreover, leakance must be of small moment at the low frequencies where the total loop resistance goes down to tens of ohms. At higher frequencies leakance might conceivably play a little part if it were extremely great. But it is suggested that a properly designed network would use resistance terminations between wires which would, according to the connections of Fig. 8, swamp all leakance effects even at very high frequencies.

It is not quite clear what Mr. Timmis means when he speaks of the attenuation caused by the network of Fig. 8. The number of such parallel connections would be few, and the condensers exist to prevent the increased attenuation at low frequencies which would be brought about if pure resistance was connected between wires. The resistance termination as designed has the double advantage of preventing the sudden rise of level of reproduction around the 4 000–6 000 cycles-per-sec. frequency band, and of raising the input impedance of the network at these frequencies. It is difficult to see, therefore, how its connection would be deleterious when it has been proved in theory and in practice to prevent large variations in level without increasing attenuation.

The idea of earthing the resistance termination at successive points was to maintain a forced balance on the system which a single centre-point earth at the transformer might not maintain. The scheme also eliminates high-frequency disturbances which may be picked up and carried via the lines from the source of disturbance to wireless aerials near their route.

The question of the "high-level link," i.e. feeders carrying voltages higher than those to be directly applied to the terminals of the loud-speakers, has been dealt with in the paper in the sense that it is shown that the theoretical advantages which Mr. Cross outlines are great, but the practical difficulties serious. Naturally, the buried cable overcomes the potential danger of giving electric shock to wiremen and consumers. But cables possess distributed capacitance and inductance and, if more than

a few miles long, may require resistance termination treatment to minimize the risk of a non-uniform potential distribution over the frequency range. This effect might, indeed, be very serious if the lines were long and wrongly terminated or not terminated at all.

Mr. Sandeman states that no mention is made of services which are based upon the use of existing telephone lines, but he should be referred to the introduction where such systems are, at any rate, mentioned. They do not appear to present any particular design problems, but they do present practical difficulties.

The disadvantages of such a system are not, as some seek to prove, that they involve the use of valves (the wireless industry flourishes, but uses a large number of valves), but because of the difficulty of securing absence of cross-talk and mutual interruptions in what is essentially a dual service. But every system, audio-frequency with telephone lines or with new networks, or carrier-frequency with existing electric power networks, have, as has been stated in the paper, much the same economic basis.

Mr. Murphy comments upon the ideology of rediffusion, being prompted to do so, no doubt, by the opening words of the paper. He makes the statement that the average listener will not support rediffusion because, although he does not use the advertised facility of a radio set to pick up all sorts of different transmissions, he still likes to

feel that he could do so if he wanted to, and therefore buys the radio set. Mr. Murphy, however, underestimates the public's intelligence; his theory is not backed up by facts. In Holland, for example, more urban listeners use rediffusion than use only wireless sets. In Hull one householder in every four gets his programmes via rediffusion. In other English towns and cities, where rediffusion has not been installed so long as in Hull, the numbers of consumers are mounting quickly and at much the same rate as they have done in Hull. Listeners apparently do appreciate the advantages of rediffusion.

I have long believed, as has been stated in the opening sentences of the paper, that wire broadcasting, whatever form it may take, has great advantages over wireless broadcasting for the distribution of broadcasting entertainment to the public. Two major and as yet unsolved (and perhaps insoluble) problems are implicit in wireless broadcasting, (i) the lack of separate channels of communication, and (ii) the interferences to wireless reception brought about by atmospheric and machine-made electrical disturbances. Both these problems are automatically solved by the use of wires instead of wireless to distribute programmes. Audio-frequency rediffusion is a very limited form of wire broadcasting, but its commercial success has shown that my opinions are supported by the facts.

DISCUSSION ON

"MEASUREMENT OF THE ANGLE OF INCIDENCE AT THE GROUND OF DOWN-COMING SHORT WAVES FROM THE IONOSPHERE."*

Prof. J. Hollingworth (*communicated*): I think there can now be little doubt, as a result of the investigations described in this paper and the recent one by Dr. Walmsley, that the short-wave transatlantic transmissions in general show an angle of incidence of 76° to 80° , a fact which is of great practical importance.

I am inclined, however, to think, apparently with Dr. Walmsley, that the mechanism causing the waves to follow this path is still very imperfectly understood. The usual idea of multiple hops, while generally giving figures of the right order, does not seem to stand up to critical analysis.

In particular, the present author shows an angle of incidence varying from 73° to 90° and ascribes this to an increase of ionization lowering the effective height of the layer. Assuming a "double hop" and a distance of 5 400 km, this involves a change in layer height from about 740 to 150 km, which seems excessive. If, on the other hand, the change is caused by changes in the number of hops or shifts of the point of reflection from the F layer to the E layer, two difficulties arise. In the first case, which goes to the root of the problem, no explanation is provided of why the great part of the energy is concentrated in a ray making a certain number

of "hops" with almost total exclusion of the others. That this can be so is, I think, unquestionable; I have had very definite proof of it in my own experiments; but a ray at 74° with a layer height of about 200 km requires 4 or 5 hops, whereas both 3 and 2 are still geometrically possible, and at present we seem to be still without definite information of the reason for this selective property. If, however, the ray shifts from one layer to the other we should expect discontinuities in the curve, of the type found by Appleton and Naismith.

Instrumentally I favour the author's method of depending on phase rather than intensity measurements, as it has practical advantages for the experimenter who is not equipped with two similar measuring sets, and its calibration and lining-up are somewhat easier. I hesitate, rather, however, at its use on stations off the designed direction, since in these positions it will receive a component of the horizontal electric force in the direction of propagation. This component is not strictly absent unless the earth is treated as a perfect conductor. It may, of course, be negligible; but as the constants of the earth at frequencies of this order are still not quite certain it may produce errors, since in a signal consisting of two circularly polarized components with opposite directions of rotation the fades are not

* Paper by Mr. A. F. WILKINS (see vol. 74, p. 582).

simultaneous on the horizontal and vertical components of the electric force. Personally I always try to avoid such difficulties by only taking observations when the ellipses on the cathode-ray tube are near their maximum values, as it so often happens that when a large steady ellipse shrinks owing to a fade it becomes unsteady and fluctuating owing to the presence of such residuals.

The statement on page 586 (vol. 74) as to the reversibility of the ray track is strictly only true if the effect of the earth's magnetic field is neglected; though the effect of this in general is probably small.

Mr. A. F. Wilkins (*in reply*): I agree with Prof. Hollingworth that the ascription of the total summer diurnal change of angle of incidence to variations in equivalent height of the layer necessitates excessively large variations of that height. The real cause of the variation of angle has been made clearer as a result of frequent 20-metre pulse emissions which have been made from Lawrenceville during the past year. These tests have usually taken place between 1400 and 1700 G.M.T., so that it has not been possible to study the variations in number and angle of incidence of the received rays throughout the whole period of normal working of these 20-metre stations. The trend of angle of incidence outside the period of the pulse tests may be deduced, however, from the seasonal trend. The outcome of these tests has been that, during a summer afternoon, the received energy is concentrated in a single group of rays of small time-separation, and it is thought that the whole group is associated with one order of multiple reflection from the F region. The angles of incidence of the measurable rays of this group often show an increasing tendency during the observation period. Towards the end of the test, lower-order multiple reflections (of larger angle of incidence) begin to appear, and experience during the year's work has shown that, with decreasing ionization over the whole path, the amplitude of these lower-order echoes increases, while the higher-order echoes decrease.

The increase in angle of incidence during the period of commercial working is thus due to a small increase in the angles of the main group of rays present in the early part of the period, followed by the effect of increase of relative strength of lower-order multiple reflections.

The variation of angle of the echoes during the early part of the transmission can be accounted for if regard is taken of the bending suffered by a ray in passing through the E region and the ionized medium which probably exists between the E and F regions. The change of angle with time will then be due to the passage of the position of maximum ionization in these regions across the Atlantic in a westerly direction. The variation in the number of echoes is due to the combined effects of E-region absorption of large angle-of-incidence rays and of electron limitation in the F region on small-angle rays. I suggest that these absorption and limitation considerations explain Prof. Hollingworth's difficulty as to why the energy is concentrated mainly in a ray making a certain number of hops.

Reduction of the records of the pulse experiments referred to has so far failed to reveal any trace of E-region echoes on the 20-metre wavelength; it would appear that absorption is far too severe to give appreciable energy from this region at the receiver. This disposes of Prof. Hollingworth's suggestion that a change of angle of incidence could be due to a shift of reflection from the F to the E region.

Prof. Hollingworth is doubtful about the utility of the method of angle-of-incidence measurement for stations off the "broadside" position. While agreeing that the aerials do, under such conditions, respond to a component of the horizontal electric force in the direction of propagation, I cannot agree that this will give rise to error in the deduced angle of incidence; because the resultant forces acting along each aerial will, in the case of one downcoming ray, be of similar amplitude but their phase differences will still be as stated on page 583 of the paper. I agree, however, that, for a signal consisting of two circularly polarized waves, the angle measurement would be liable to error, but this would be so even if the signal were incident in the "broadside" direction. The method described is strictly accurate on continuous-wave transmissions only in the case of one downcoming ray; it has, however, been found that, in the presence of several rays, the average of many observations taken over a short period approximates to the angle of the strongest ray measured on a subsequent pulse transmission.

AN EXAMINATION OF THE CAUSES AND NATURE OF THE INTERFERENCE TO WHICH THE WIRELESS COMMUNICATIONS OF THE MERCANTILE MARINE ARE SUBJECTED.

By Commander J. A. SLEE, C.B.E., R.N., Member.

(Paper first received 22nd December, 1933, and in revised form 3rd April, 1934; read before the WIRELESS SECTION 2nd May, 1934.)

SUMMARY.

This paper sets on record the steps which have recently been taken to analyse the various types of interference to which the wireless communications of the mercantile marine are subjected.

It deals with the interference caused by broadcasting and the interference caused by transmissions from other ships, both from the point of view of telegraphic communications and from that of direction-finding.

INTRODUCTION.

The wireless communications of the mercantile marine are subject to regulations issued by the administrations of the maritime nations, which in turn are governed by the relevant parts of the General Radio Communication Regulations attached to the current International Telecommunication Convention, which came into force on the 15th January, 1933.

These regulations lay down the purposes for which the various bands of frequencies may be employed. Certain bands are allocated exclusively to the mercantile marine, others to mobile services generally, and some are shared between mobile and other services. The regulations also set limits to the use of various types of emissions, and lay down the signalling procedure to be used.

The distribution of wavelengths given in the Madrid Regulations is not very different from that previously in force which had been worked out at the Radiotelegraphic Conference, Washington, in 1927, and a certain amount of difficulty is experienced in carrying out the communications of the mercantile marine owing to the interference which exists, especially in certain areas near the coasts of Europe and the United States. The object of this paper is to explain the steps which have been taken to analyse the sources of this interference.

The objects of marine wireless communication are: (1) The safety of life at sea. (2) The assistance of navigation by means of direction-finding, weather reports, time signals, etc. (3) Messages concerning the movements and navigation of ships. (4) Private telegraphic or telephonic communication.

The International Regulations permit the employment of certain bands of frequencies by the mercantile marine for the purposes shown in Table 1. For the sake of brevity, only the most important aspects of the case are quoted. For full details reference should be made to the Regulations.

In addition to the parts of the subject discussed in this paper there is also a vast amount of communication on frequencies between 1 500 and 2 000 kilocycles per

sec., and on frequencies of the order of 8 000 kilocycles per sec. and above.

The whole question therefore divides itself up into the following parts. (a) Interference with so-called "long wave" communications, of frequencies between 110 and 160 kilocycles per sec. (b) Interference with so-called "medium wave" communications, of frequencies between 365 and 515 kilocycles per sec. (c) Interference with direction-finding work (285-320 and 365-385 kilocycles per sec.).

(1) GENERAL SITUATION.

The 110-160 kilocycles per sec. Frequency Band.

There are a number of broadcasting stations within or near the edge of this band whose emissions may interfere to a greater or less extent with communications. The traffic is telegraphic, and only continuous-wave emissions are used. It may be interfered with either by the heterodyne beat of the carrier or by the sound of the modulated speech or music. As signals in this wave band are habitually read from field strengths as low as 2 microvolts per metre, it follows that the interference range of the powerful broadcasting stations is very great.

When the speech is perceptible, little if any advantage can be gained by the use of low-frequency tuning, but at greater distances advantage can be taken of low-frequency tuning and the possibility of using the silent zone of beat reception.

There is also the problem of interference caused by the communications of other mobile stations.

The 365-515 kilocycles per sec. Frequency Band.

The problem of interference in this wave band is much more difficult and much more important. The "distress and calling" wave (500 kilocycles per sec.) is situated near one edge of this band, and not only must telegraphic communication be carried out on this frequency but the satisfactory working of the automatic instrument known as the "auto-alarm" must also be possible. Direction-finding is also carried out to a small extent in this band of frequencies.

The communication is telegraphic, and all kinds of emissions are used, Type B (i.e. spark) being the most numerous. There are a number of broadcasting stations whose emissions are likely to interfere more or less seriously in this band, and there is also the problem of interference caused by other mobile stations.

Interference—both telegraphic and telephonic—with communications on the other mobile bands is not for the moment of such great importance, and for the sake of

TABLE 1.

Frequency band	Allocation	Employment
kilocycles per sec. 110-160	Mercantile marine (exclusively)	Type A ₁ only. Used chiefly for the private traffic of large liners.
285-320	Beacon service	Low-power transmitters working for the express purpose of allowing ships fitted with direction-finders to observe the bearings of the beacons, and thus obtain a position.
365-385	Direction-finding service	Ships wishing to know their position transmit on 375 kilocycles per sec. in order that coast stations may observe the bearings and inform the ship of her position. Also used to a small extent for traffic.
400-485	Mobile service	Not exclusive, but very little used except by ships. Used for all general ship-to-shore and shore-to-ship traffic.
485-515	Ships exclusively	Guard band to the distress wave (500 kilocycles per sec.). Also used for calling; carries a great deal of traffic, especially in distant parts of the sea.

brevity this part of the subject has been left almost untouched.

Interference with Direction-Finding Work.

Interference with direction-finding is extremely important, as this method of obtaining bearings is now used so very extensively for the purpose of navigation. The majority of the work is done in either the 365-385 kilocycles per sec. band, or in the special beacon band of 285-315 kilocycles per sec. This subject is somewhat complicated by the fact that it is necessary to take into account the difference of bearing between the wanted and unwanted signals, as well as all the characteristics of the receivers and the strength of the interfering field.

So far, the subject has only been fully analysed for European waters. The methods adopted and the results obtained form the subject of Section (4) of this paper.

(2) DETAILS OF INTERFERENCE IN THE 110-160 KILOCYCLES PER SEC. FREQUENCY BAND.

In order to analyse the probable interference, two steps have been taken: (a) to ascertain the characteristic response curves of the receivers likely to be used, and (b) to ascertain the probable field strength of the interfering field. Traffic carried on this band of frequencies is revenue-earning, and good apparatus and highly skilled operators can be expected. There are a large number of types of receivers in use at sea, and Fig. 1 shows a representative high-frequency response curve for the type likely to be used in this band of frequencies. It will be seen that its slope is about 3 decibels per kilocycle per sec. The use of low-frequency tuning improves matters considerably at distances great enough to render telephonic speech inaudible, but it is of little

or no service when speech or music can be distinguished. Indeed, in the case of music, low-frequency tuning is probably worse than useless. It may be thought that the slope of the curve shown in Fig. 1 is not steep enough for modern requirements, but it is the existing figure and has been arrived at after many years of trial and error. It is probable that in the near future conditions may

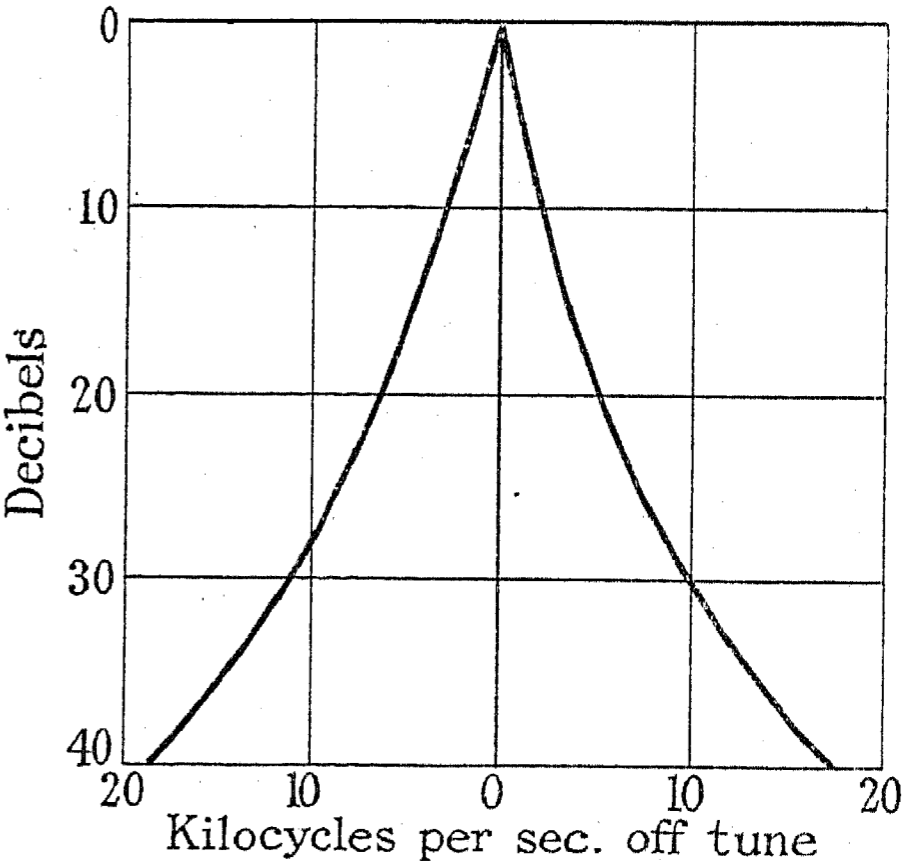


FIG. 1.—Response curve, average liner's receiver.

render desirable the use of receivers having better powers of selection. Several types of new receivers are available having an effective slope of about 5 decibels per kilocycle per sec., but very few of these are yet in service.

The following method has been adopted for determining rapidly the probable field strength of the emission of any of the very numerous broadcasting stations at any particular point. A large map of European waters is

selected and the existing and proposed broadcasting stations are plotted on it, the wavelength (and frequency) of each being noted. The intended aerial power is also known, and as it has been decided to accept as the probable efficiency of any aerial used for broadcasting the figure of 66 per cent, unless definite information can be obtained to the contrary, the radiated power can be arrived at. During the Radiotelegraphic Conference at Madrid, propagation curves were circulated which were due to the work of a special committee consisting of

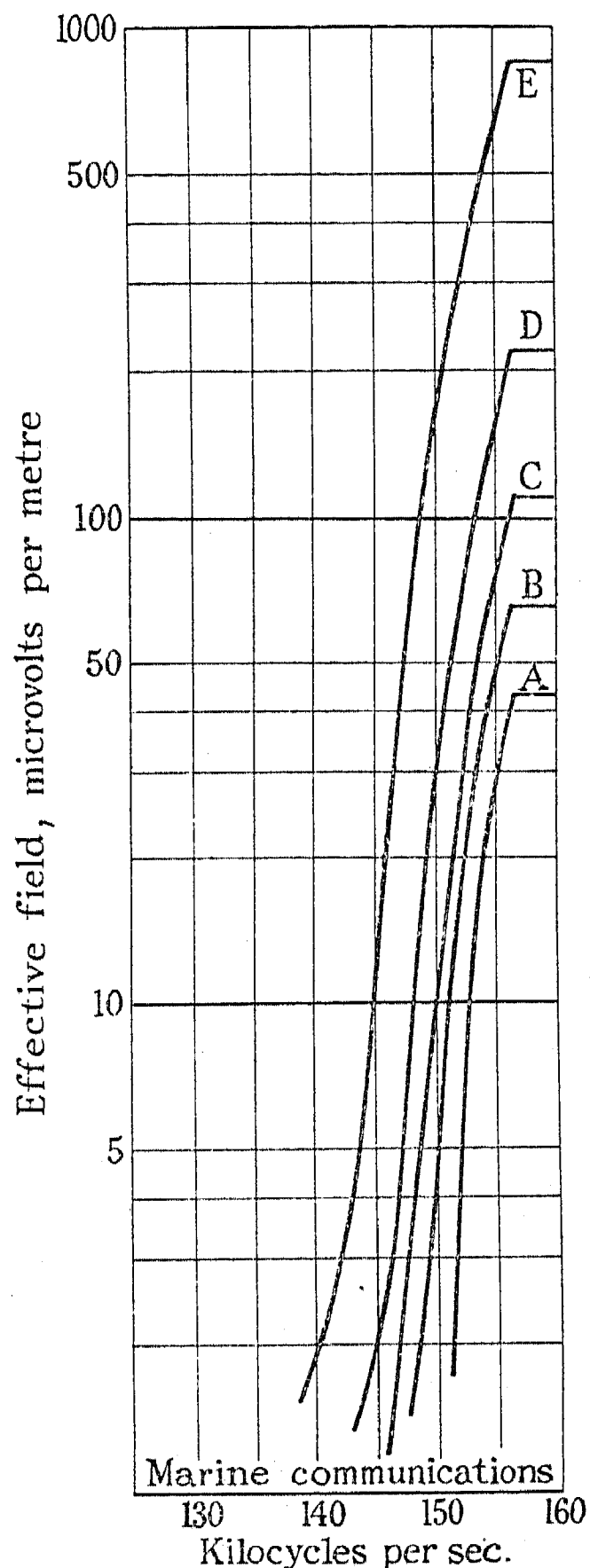


FIG. 2.—Anticipated interference from Brasov; 150 kW, 160 kilocycles per sec.; average liner receiver.

- A: at 5 000 km (2 600 nautical miles).
- B: at 4 000 km (2 100 nautical miles).
- C: at 3 000 km (1 560 nautical miles).
- D: at 2 000 km (1 100 nautical miles).
- E: at 1 000 km (550 nautical miles).

Dr. Van der Pol, Mr. T. L. Eckersley, Dr. J. H. Dellinger, and Dr. Le Corbeiller. These give the field strength under various conditions per kilowatt radiated; thus if the field strength per kilowatt at any distance is multiplied by the square root of the number of kilowatts radiated, the probable field is at once obtained. The square root of the radiated power is inserted on the map against each station. For lack of a better name this figure is called the "transmission factor" (T.F.).

A scale is then made out marked on one edge with the kilometre scale of the map and on the other edge with the number of microvolts per metre per kilowatt

radiated, as taken from the Madrid curve for mean night field strength. The latter is the same for all distances, over land or water, and for all the frequencies under discussion. To obtain the mean night field strength at any place or distance it is only necessary to read off this figure from the scale and multiply by the transmission factor.

During the Broadcasting Conference at Lucerne this curve was extended by a sub-committee consisting of Dr. Van der Pol, Dr. Harbich, Dr. P. David, Commander Bion, Mr. N. Ashbridge, and Mr. Shostekovitch. The figures quoted in this paper are derived from the corrected curve.

Working from the field strength thus obtained and from the response curves of the typical receiver, it is easy to arrive at "probable interference curves" such as those shown in Fig. 2. In this, 4 kilocycles per sec. have been allowed each side for modulation when the field is strong, and this allowance has been reduced progressively to zero at the distance at which the field is reduced to 10 microvolts per metre. This somewhat arbitrary method has given results which coincide quite well with reports from ships at sea. Fig. 2 shows the expected interference from the new 150-kW station at Brasov, working on 160 kilocycles per sec.

These figures indicate the probable state of affairs with regard to receivers in ships. In coast stations better conditions exist, because the noise level is much lower and the great benefits of directional reception can often be employed. It must be realized, however, that the field strength required to produce a readable signal at the coast station is about one-thousandth of that usually stated to be necessary to provide a broadcast "service," and the power radiated by ships is measured in watts as compared with the kilowatts radiated by the large broadcasting stations.

In this band of frequencies the problem of interference between mobile stations is not very serious. The coast-station frequencies are sufficiently separated to prevent interference, and most of the traffic consists of messages from coast stations to ships, which are sent on the coast stations' waves, or of messages from ships to coast stations, in which case the ships must take their turn and use frequencies as directed by the coast station. This matter being one of regulating communications within one particular service, it can be satisfactorily dealt with by administrative service organization.

The signals are all sent on waves of Type A₁, and note filters can be used with great advantage.

(3) DETAILS OF INTERFERENCE IN THE 365-515 KILOCYCLES PER SEC. FREQUENCY BAND.

Work of Lucerne Conference.

The question of interference with the mercantile-marine communications in the medium-frequency band (365-515 kilocycles per sec.) is much more difficult, as not only has the vitally important matter of distress working to be considered and protected, but also the proper working of the automatic alarm signal apparatus must be taken into account.

Distress work has to be carried out by all ships, and receivers of many types have to be allowed for. After a

great deal of discussion in technical sub-committee at Lucerne, a receiver having the general characteristics shown in Fig. 3 was accepted as representing the normal type. Receivers of this quality just permit communication to be carried out in spite of the present severe interference caused by broadcasting stations working near the lower limit of the frequencies allotted to them. There are, however, a few small areas in European waters where communication is very difficult. The adequate screening of receivers against direct excitation is very important.

The method used for determining the interfering field strength from any station at any point is similar to that already explained, but there is an added complication due to the simultaneous interference on many neighbouring frequencies, a subject which does not lend itself to simple explanation.

In dealing with this problem the first consideration was given to the working of the auto-alarm. This is an

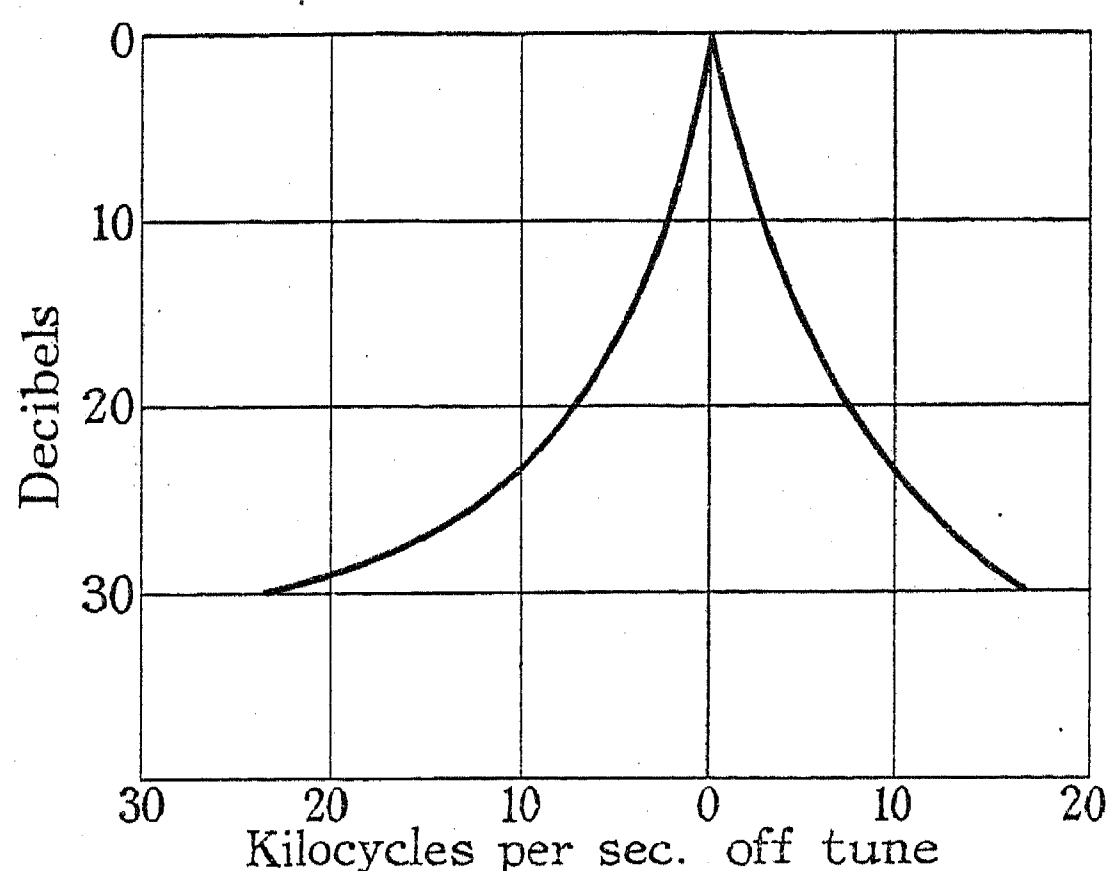


FIG. 3.—Response curve, average ship's receiver.

instrument used in merchant vessels which are compulsorily fitted with wireless but which, according to the Safety of Life at Sea Regulations, are not compelled to maintain constant human watch. It consists of a receiver which must possess a stated minimum degree of receptive power on any frequency between 487.5 and 512.5 kilocycles per sec., and of a selector whose duty it is to pick out the International Alarm Signal from the medley of other signals which almost constantly operate a receiver of such characteristics. When considering this subject the effect of the combination of several interferences assumes great importance. The wide band of frequencies over which these receivers must be responsive makes it almost impossible to give the outer sides of the resonance curve a very sharp slope.

At the Radiotelegraphic Conference at Madrid it became apparent that the allowance of frequencies exclusively allotted to broadcasting was insufficient for European requirements, and therefore a conference was held at Lucerne in June, 1933, to search for some agreed method of admitting broadcasting services in the bands of frequencies allotted to "mobile" services in derogation of the Madrid Regulations.

After taking into consideration the characteristic curves of some typical receivers of different manu-

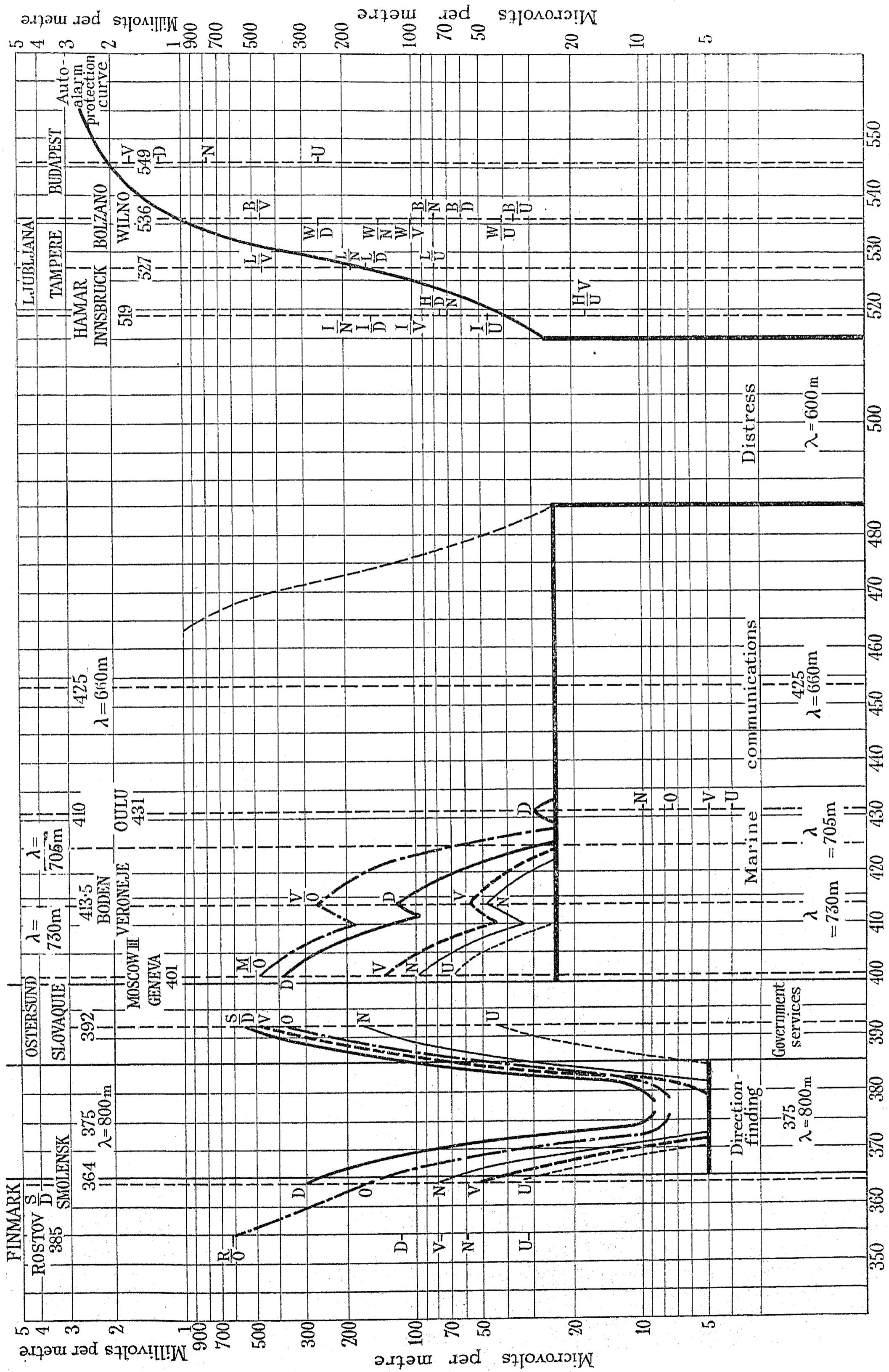
facture, the probable maximum effective height of aerial of ships likely to use this device, and the injected voltage at the input of the receiver necessary to operate the selector, it is possible to arrive at a curve such as that shown on the right-hand side of Fig. 4. This curve is constructed as follows. The framework of the curve is marked with vertical lines representing the bands of frequencies allotted to the mobile services into which such derogations are to be considered. The horizontal lines represent field strength, the scale being logarithmic. The band of frequencies from 485 to 515 kilocycles per sec. is allotted by international convention exclusively as a guard band to the International Distress and Calling Wave (500 kilocycles per sec.), and in consequence the Lucerne Conference agreed that the interfering field in this band should be zero. Allowance having been made for a factor of safety, the permissible interference field at each edge of this guard band was fixed at 25 microvolts per metre, and from these two points the curves shown in the right-hand part of Fig. 4 can be drawn. It can be assumed that if the field strength of signals from any station, plotted on the frequency of that station, falls above this curve, interference is probable, and that if it falls below this curve, interference is not probable. The field strengths, calculated as described above, of those stations which, according to the Lucerne Plan, are likely to cause interference, have been plotted. Each position is marked with two initials, the upper being the initial letter of the station and the lower the initial letter of the district for which the field strength was calculated.

Fig. 4 indicates the probability of interference from a few stations, looking at the matter from a theoretical standpoint. The geographical position of most of these stations, and the nature of the country surrounding them, make it most improbable, however, that any serious inconvenience will be experienced.

As marine communications have to take place all over the navigable surface of the sea it follows that any limitations of field strength which may be legislated for, must be measured at the point on the coast nearest to the interfering station.

At the low-frequency edge of the so-called "distress band" there are no powerful broadcasting stations. It is, however, necessary to arrive at some figure for the permissible interfering background. Experience shows that signals read in this band are frequently derived from a field as low as 12 microvolts per metre, and, making a generous allowance for the power of a professional telegraphist to over-read the wanted signal through a noisy background, an interfering field level of 25 microvolts per metre was agreed upon.

Passing on to lower frequencies, we reach the band from 365 to 385 kilocycles per sec. in which a direction-finding service is carried out by the coast stations. The exigencies of the direction-finding service demand a much lower background-noise level, and so the figure of 5 microvolts per metre was agreed upon. The field strength (mean night value) of the stations which, according to the Lucerne Plan, are most likely to interfere with this service, have been plotted as already described. The probable interference to be expected from these stations is shown by applying the response curve of the typical



Kilocycles per sec

Fig. 4.—Probable interference fields.

- Field strength at Danzig.
- Field strength at Odessa.
- Field strength at Venice.
- Field strength at Norddeich.
- Field strength at Ushant.

receiver likely to be used for the service in question. The results are shown at the left-hand side of Fig. 4.

The question of interference with direction-finding is dealt with more fully later in this paper, but it is clear from the curves that at night direction-finding by coast stations using the 365–385 kilocycles per sec. band will be very difficult in the Southern Baltic, and almost impossible in the Black Sea. There is no reason why this service should not be carried out at higher frequencies in these areas.

During the Conference at Lucerne it was necessary to examine rapidly the probable interference to be expected from any station, and in order to apply the methods just described with sufficient speed the following system was adopted. A long framework similar to that of Fig. 4, but on a large scale, was prepared with the

station direction-finding service was under discussion, similar curves were used derived from the response curves of typical coast-station direction-finding receivers. Fig. 4 is a reproduction on a more convenient scale of the interference diagram to be expected from the arrangement which was finally agreed upon.

The foregoing gives an outline of the theoretical methods which were used at the Lucerne Conference for assessing the interference with marine communications likely to be caused by broadcast services. The general result of reports from sea shows that they are fairly correct. It is probable that from the instrumental point of view the interference is often rather worse than that anticipated, but that the skill of the telegraphist in over-reading and in manipulating his instruments is rather greater than that allowed for.

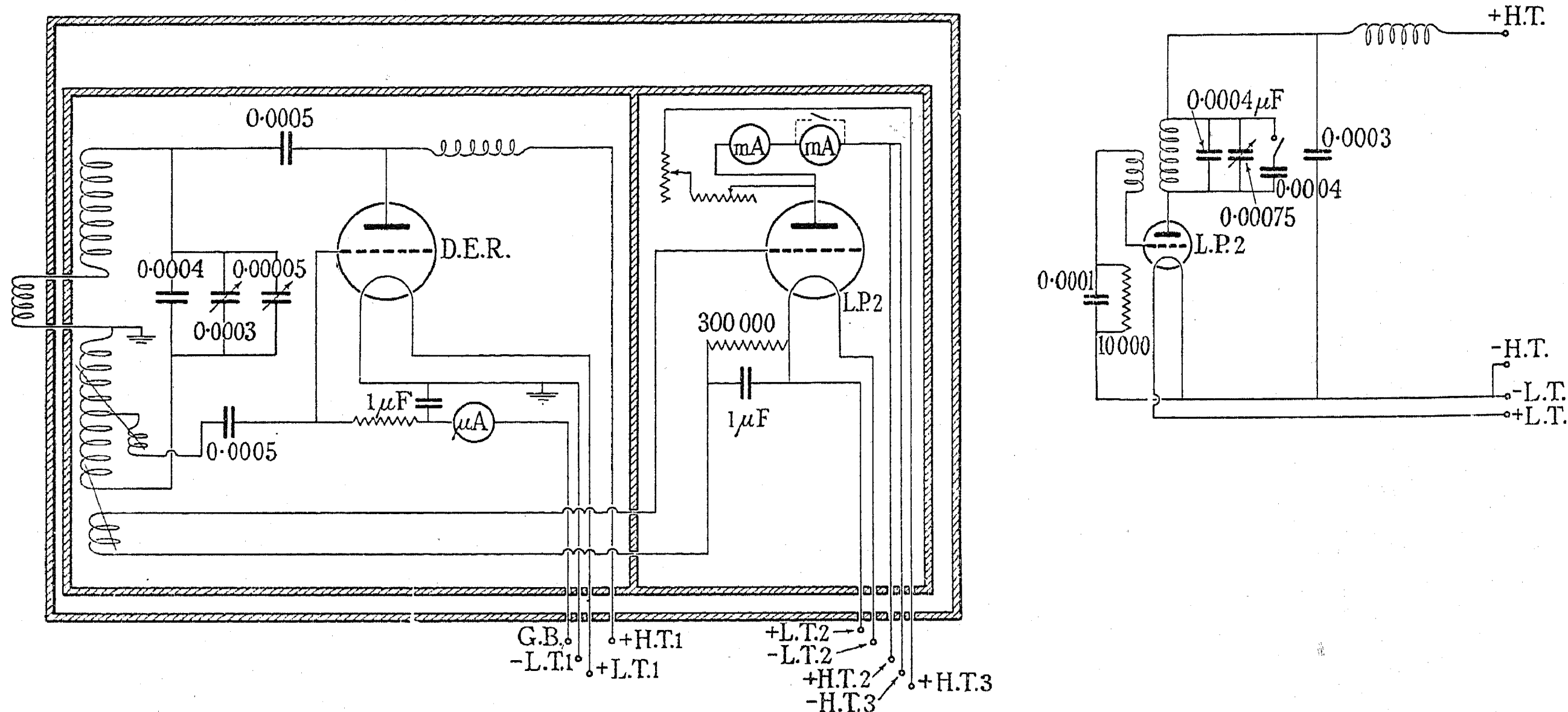


FIG. 5(a).—Low-decrement instrument and (on right) wavemeter.

vertical lines showing each kilocycle per sec. of frequency, and the interference curves as so far described were marked on it. The field strength was shown by horizontal lines ruled on a logarithmic scale. The boundaries of the various services and the permitted spark frequencies were also marked. A narrow slip of paper was prepared for each station under discussion, having the field-strength scale marked on it, on which the mean night field at selected places could be marked in various colours. Generally speaking, the places selected were Danzig, Odessa, Norddeich, and Ushant. These slips were moved about over the chart, and the interfering field due to each station on its own frequency was at once apparent. To examine any proposed allocation it was only necessary to mark slips according to the power of the stations and lay them on the frequency proposed. Curves derived from the response curve of a typical ship's receiver were drawn to the same scale, and these when laid beside the vertical strips showed the effective interference field on other frequencies.

When the question of interference with the coast-

The net result is a very fair agreement with the theoretical arguments so far stated.

Investigation of Interference Caused by Spark Transmitters.

Turning to the interference with marine communications caused by other stations taking part in the same service, we find that the main source of trouble is that the vast majority of the ships are equipped with spark apparatus. Five spot frequencies are allowed by the regulations to be used by apparatus of this type.

The spectrum of spark emission is very wide, and experiments are being carried out with the view of reducing its width. In the old days, when spark apparatus was of primary importance, we had no means of accurate measurement, and when suitable measuring instruments were first introduced it did not seem to be worth anybody's while to make a careful examination of this subject.

Three sets of investigations have recently been undertaken on this subject: (a) the examination of the tuning of the transmitting circuits, (b) the examination of the

spectra of various transmitters in the laboratory, and (c) the examination of the spectrum by field-strength measuring instruments at a distance.

With regard to (a), the tuning of the transmitting circuits has been examined by means of a special delicate wavemeter of the absorption type, in which the point of resonance is indicated by the occurrence of maximum feed current. The instrument used has a scale of about 2 kilocycles per sec. per division of condenser scale, and the change of feed current at resonance exceeds 20 per cent. It permits of an accurate and rapid determination of the resonance frequency of the circuit under examination, but curves derived from observations taken by this instrument cannot be regarded as resonance curves. Details of the instrument are given in Fig. 5(a), and Figs. 5(b) and 5(c) show some specimens of the results obtained by its use.

When working with this instrument it was noticed

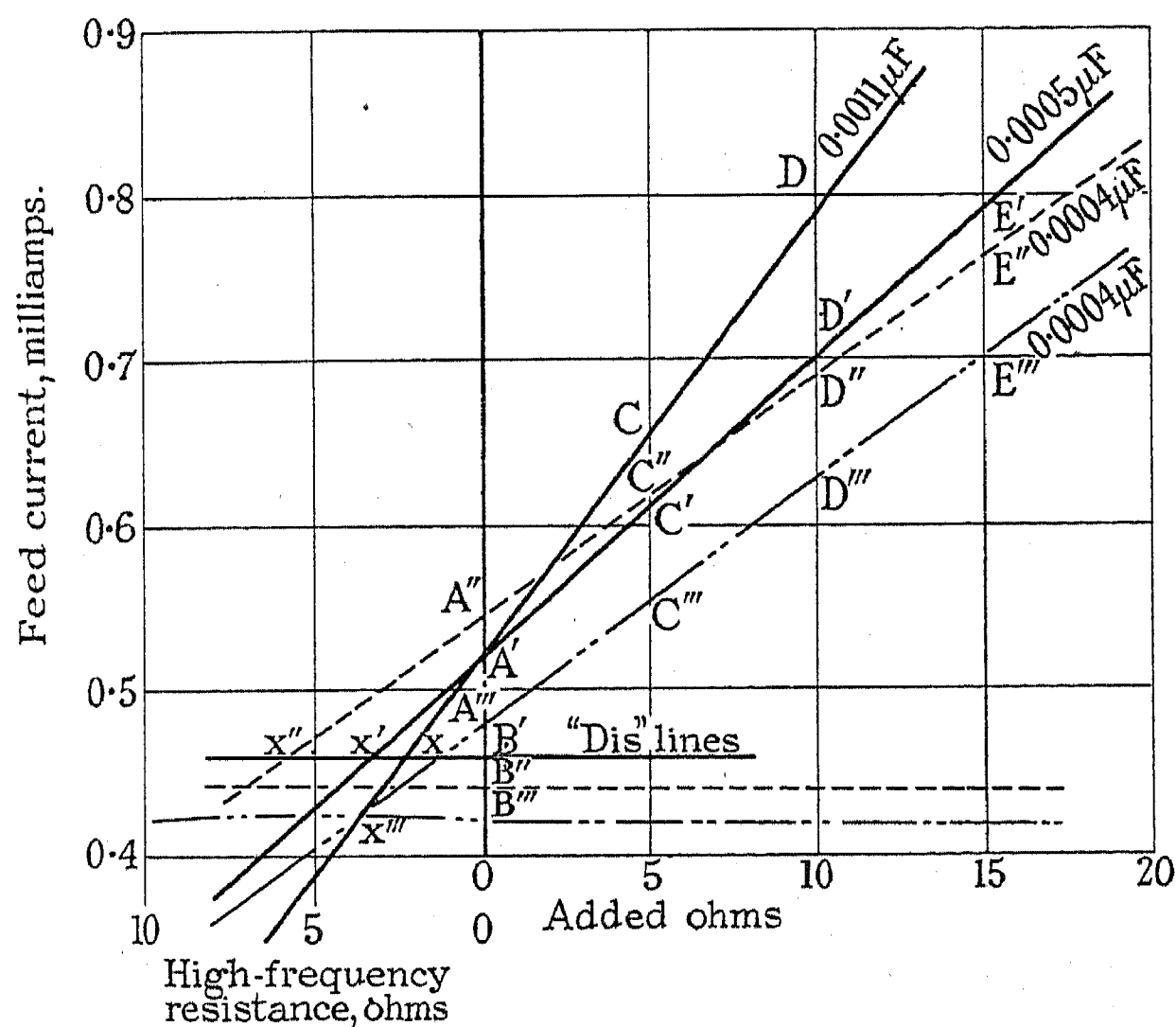


FIG. 5(b).

that if the coupling between the wavemeter coils and the circuit under examination is just not tight enough to produce the effect of "stabilizing," the change of feed current at resonance when the circuit under examination is or is not completed gives some indication of the high-frequency resistance of the circuit under examination. This property appears to provide a method of measuring, or at least comparing, the resistance (and possibly also the capacitance) of such a circuit as a ship's aerial. Further trials are in progress to determine whether the results obtained are sufficiently consistent to be of practical value.

Diagrams of the sort shown in Figs. 5(b) and 5(c) are constructed in the following way. The wavemeter is placed close to the circuit to be measured, and is moved into the position where stabilizing just does not take place. The feed current at resonance—i.e. the maximum current obtainable without stabilization—is noted (A), as also is the feed current with the wavemeter setting unchanged when the circuit to be measured is disconnected (B). The feed-current value for B is plotted as an abscissa, and is called

in the diagram the "dis" line. The feed-current value for A is also plotted, and the ordinate through it is called "zero added ohms." Various values of known resistance are then included in the circuit under examination, and the feed currents at resonance when only just clear of the stabilizing point are noted (C, D, E, etc.). The position of the wavemeter must, of course, be altered for each measurement.

If the values of C, D, etc., are plotted, the abscissæ being "added ohms" and the ordinates the feed-current values of C, D, etc., the points are found to lie on a straight line. If this line is produced through B until it cuts the "dis" line, say at x , the distance from x to the "zero added ohms" ordinate should represent the inherent high-frequency resistance of the circuit under examination, using the same scale as that on which the known values of added ohms are plotted.

It has also been noticed that changes in the capacitance

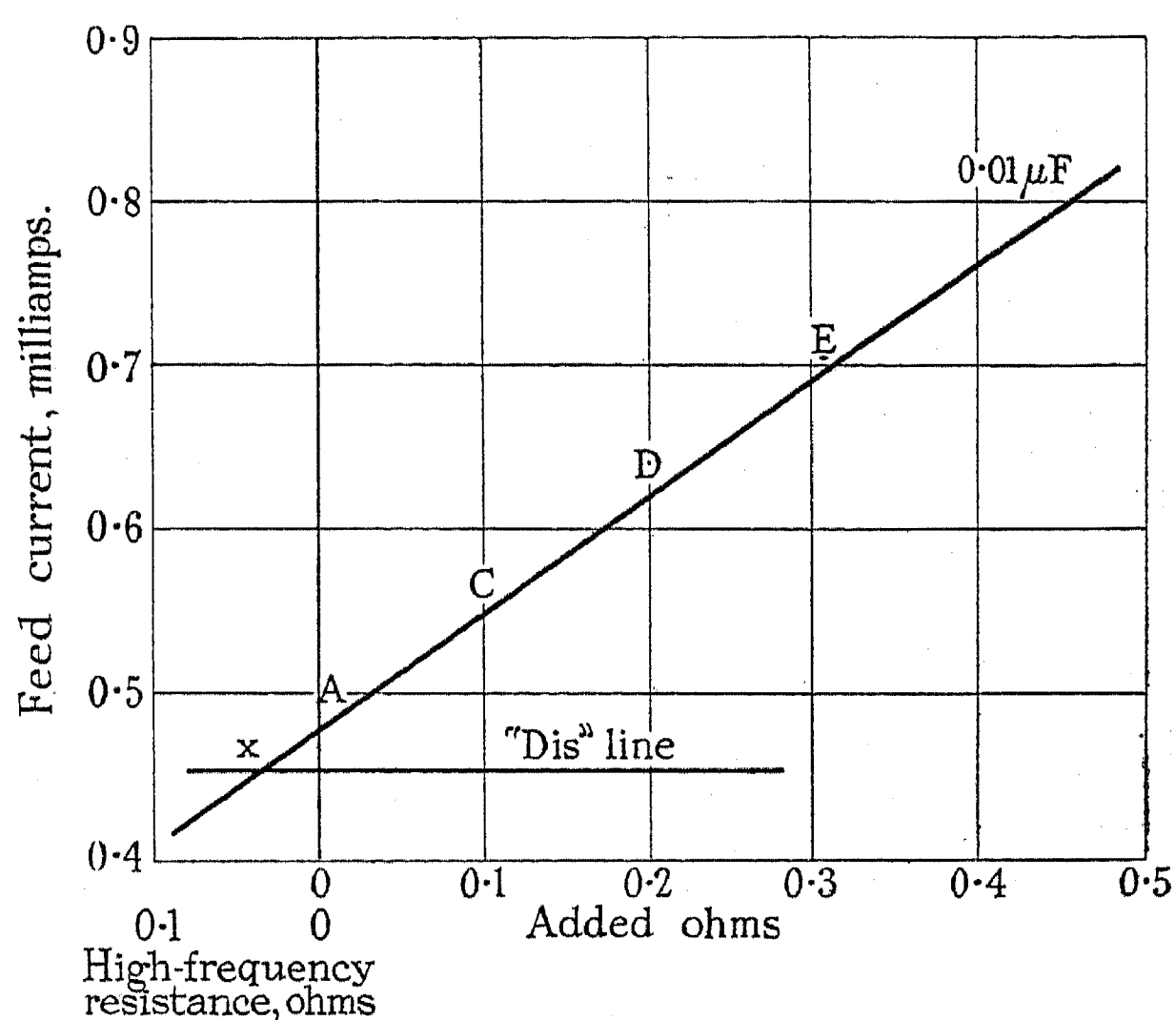


FIG. 5(c).

of the circuit under examination cause consistent changes in the angle of slope of the line A C D E, and this angle may therefore give a measure of the capacitance of the circuit under test.

Fig. 5(b) shows a plot of the readings taken on three circuits of substantially the same frequency, and Fig. 5(c) is a diagram obtained from a circuit of very different capacitance; in fact it was the primary circuit, instead of the aerial circuit, of the old spark transmitter referred to in this paper.

The obvious limitations to this method of measuring high-frequency resistance are the fact that it is not always possible to get the coupling between the wavemeter and the circuit under examination tight enough to reach the verge of stabilization, and the fact that a certain amount of practice is necessary to make certain of taking the measurements when only just short of the stabilizing point.

With regard to (b), in order to obtain the spectra of the energy emitted by various transmitters a special very carefully screened measuring instrument was made. It is so arranged that its decrement is variable at will, the

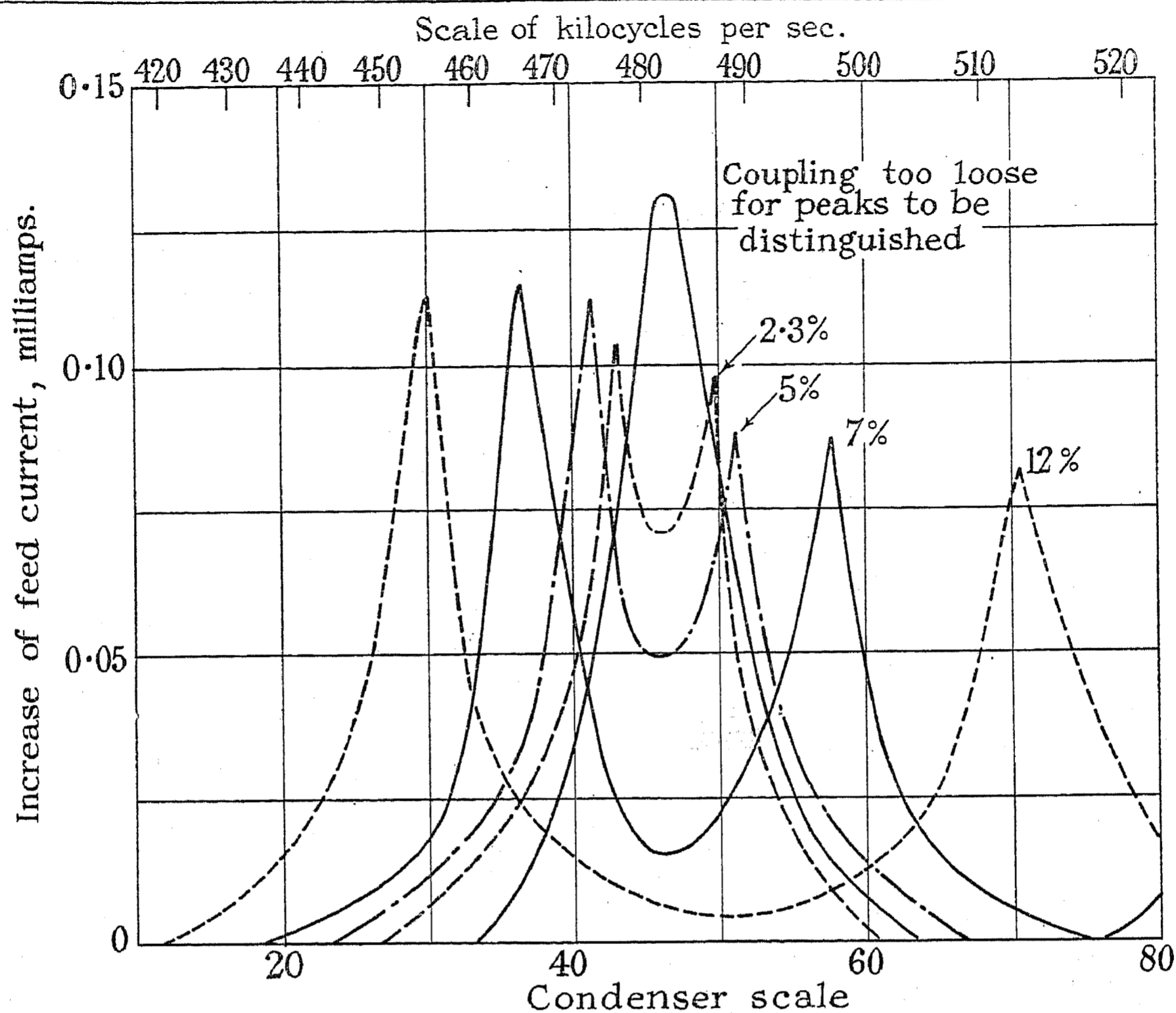


FIG. 6(a).—Wavemeter curves of old spark set.

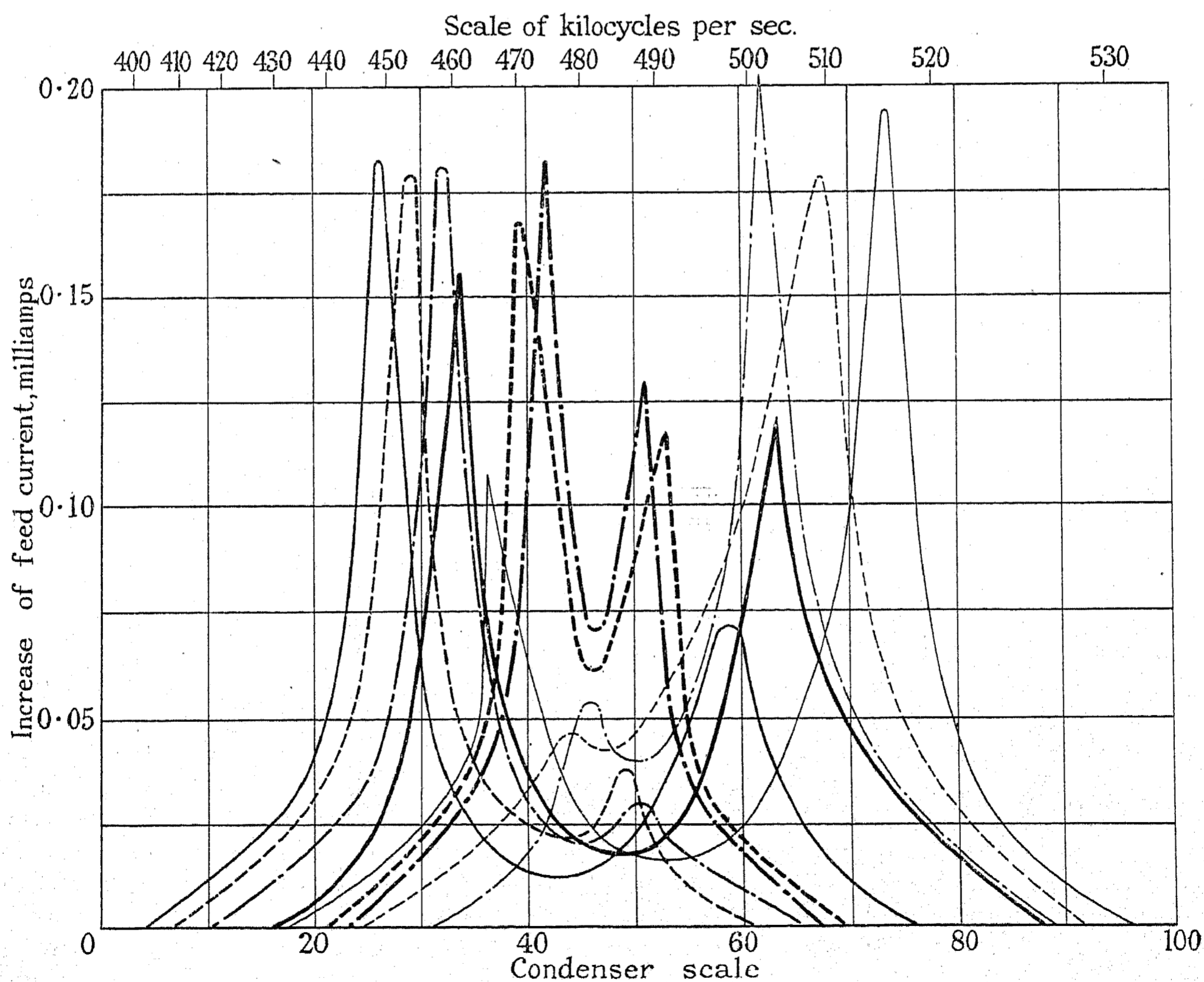


FIG. 6(b).—Wavemeter curves with grossly mistuned aerial.

— 481 kilocycles per sec., coupling 9 per cent.	--- 481 kilocycles per sec., 4.1 per cent.	--- 481 kilocycles per sec., 2.6 per cent.
— 462 kilocycles per sec., coupling 9 per cent.	--- 462 kilocycles per sec., 4.1 per cent.	--- 462 kilocycles per sec., 2.6 per cent.
— 499 kilocycles per sec., coupling 9 per cent.	--- 499 kilocycles per sec., 4.1 per cent.	--- 499 kilocycles per sec., 2.6 per cent.

least decrement obtainable giving a response curve such that a departure from resonance of 200 cycles per sec. in 500 kilocycles per sec. causes an attenuation of 6 T.U. With this instrument, details of which are shown in Fig. 5(a), the energy envelopes of several different sets were explored. The decrement of this instrument is dependent on the amount of reaction, and to keep the decrement reasonably constant over the wide range of frequencies covered by the spark spectrum the reaction must be re-adjusted at frequent intervals. It was usually reset every 5 kilocycles.

With regard to (c), it is exceedingly difficult to make field-strength measurements in the presence of the almost

show two peaks with any coupling greater than 1 per cent, no sign of two peaks can be discovered in the spark spectrum. The side peaks due to the modulation of an interrupted continuous-wave (I.C.W.) emission are quite clear.

Fig. 7(a) shows the spectrum obtained under varying conditions of coupling for equal alternator powers; the spectra of a quenched set and of an I.C.W. set giving aerial current equal to the optimum obtainable with the non-quenching spark set are also shown for purposes of comparison.

When using the least available decrement it is reasonable to suppose that the graph obtained is a close approxi-

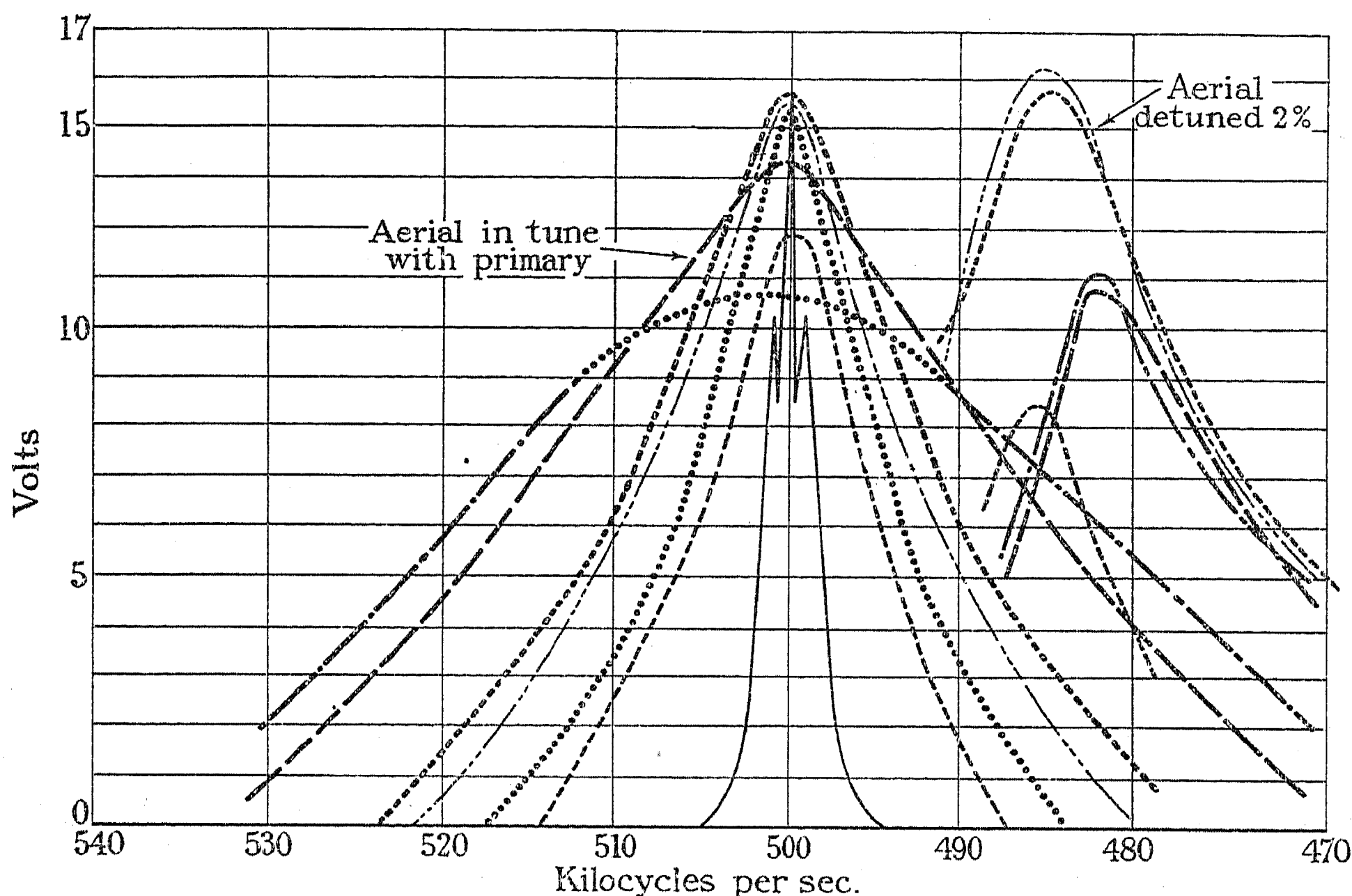


FIG. 7(a).—Emission of spark transmitter.

— — — — —	Non-quenching, 10 per cent coupling.	Aerial amps.: (tuned) 1.8, (detuned) 1.6.
— — — — —	Non-quenching, 8 per cent coupling.	Aerial amps.: (tuned) 1.8, (detuned) 1.6.
— — — — —	Non-quenching, 6 per cent coupling.	Aerial amps.: (tuned) 2.2, (detuned) 2.1.
— — — — —	Non-quenching, 4 per cent coupling.	Aerial amps.: (tuned) 2.2, (detuned) 2.1.
— — — — —	Non-quenching, 2 per cent coupling.	Aerial amps.: (tuned) 1.5, (detuned) 1.0.
.....	Q.G.	
—————	I.C.W.	

constant signalling which is going on at the important frequencies. The small number of measurements which have been obtained agree fairly well with the curves shown in Fig. 7(a). These were obtained with the measuring instrument mentioned above, set to its lowest decrement, when an old spark set was transmitting; and also when the aerial was deliberately mistuned about 2 per cent. When exploring the spectrum of spark emission from non-quenching transmitters, there is considerable difficulty in obtaining consistent measurements if the coupling between the primary circuit and the aerial circuit is tight. It is not possible to observe the crest of the curve with the instrument set to its lowest decrement. For this reason the crest of the 10 per cent coupling curve is shown dotted, indicating its approximate position.

Although the exploration with a wavemeter of the resonance conditions of the transmitting circuits will

mation to the graph of the actual spectrum, but this will not help us to investigate the problem of interference when using existing receivers. To do this, a typical marine receiver has been used, the indicating device being a suitable galvanometer inserted in the anode circuit of the low-frequency stage. The change in current gives a measure of the sound in the telephones, and is measurable for a signal which is no more than easily readable. For weaker signals the basis of measurement must be audibility, and for this reason the flanks of the curves are shown dotted. With this arrangement the curves shown in Fig. 7(b) have been obtained, and these give a good idea of the conditions likely to be experienced. When using this instrument it is necessary continually to adjust the reaction. In Fig. 7(b) the spectrum as observed by a marine receiver is shown for a non-quenching spark transmitter using various couplings, a quenching transmitter of ordinary quality.

and an I.C.W. transmission, the modulation being about 90 per cent and the modulation frequency about 1 000: when taking these measurements the aerial current was maintained constant for all types of emissions.

From these curves it is possible to derive further

points at which the effective field strength will be reduced to some non-interfering value, which for the purposes of ordinary morse communications can be taken at the previously-quoted value of 25 microvolts per metre. A curve through these points will give an "interference

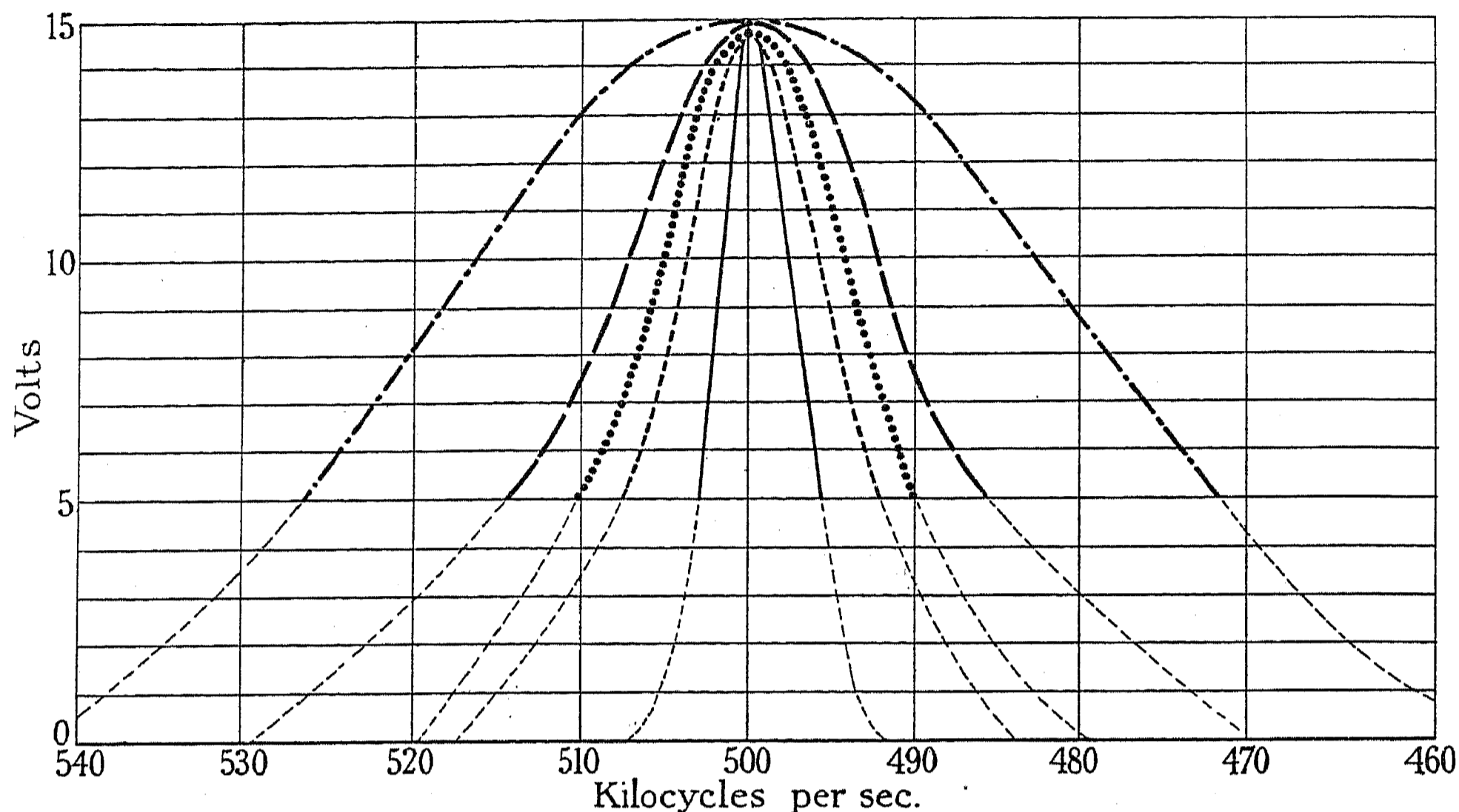


FIG. 7(b).—Emissions as observed with a typical marine receiver. Aerial current the same in all cases.

— — — — — Non-quenching, 10 per cent coupling.
 - - - - - Non-quenching, 5 per cent coupling.
 - . - . - Non-quenching, 2 per cent coupling.
 Q.G.
 ————— I.C.W.

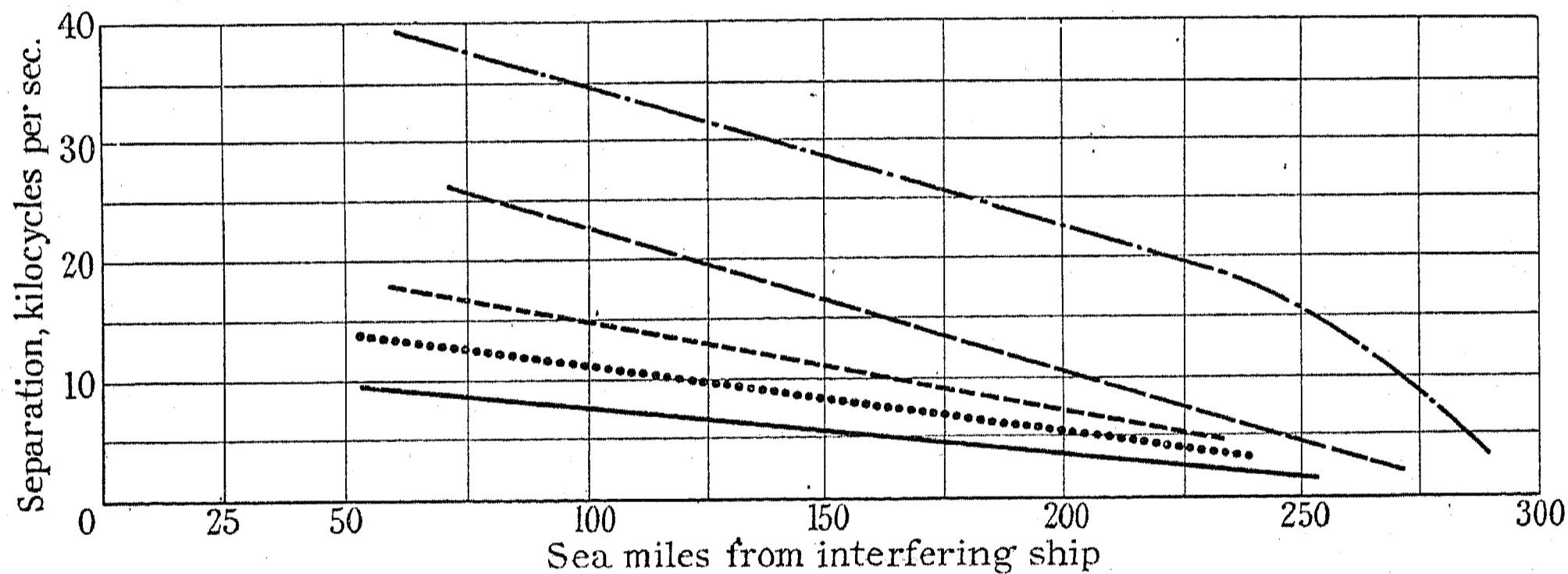


FIG. 7(c).—Derived interference curve. Distance from interfering ship to reduce effective field to 25 microvolts per metre. "Typical" receiver and various types of emissions.

— — — — — 10 per cent coupling.
 - - - - - 5 per cent coupling.
 - . - . - 2 per cent coupling.
 Q.G.
 ————— I.C.W.

curves, such as those of Figs. 7(c) and 7(d), which will show the extent of the probable interference. Such curves can only be regarded as approximations to the average conditions, because there are so many uncertain factors. This is especially the case with tightly-coupled spark emissions. These curves are constructed in the following way. The frame is drawn having as abscissæ the distance in nautical miles, and as ordinates the separation in kilocycles per sec. By applying one of the graphs in Fig. 7(b) and the mean night field strength over sea per 20 watts radiated, we can plot a series of

curve" for any particular type of transmitter and receiver (see Fig. 7c).

A curve can be constructed in a similar way showing the position between two similar transmitters at which there will be equality of signal strength for different separations, assuming the use of the "typical" receiver.

Curves derived in this way are of too speculative a nature to be regarded as certain predictions, but reports from sea indicate that they are fairly good approximations.

An examination of Fig. 7(a) demonstrates that, from

the point of view of both range obtainable and off-tune interferences, it does not much matter whether or not the primary of an unquenched spark transmitter is exactly in tune with its aerial.

The graphs also show an optimum transmitter coupling which lies between 4 and 6 per cent; looser couplings imply a serious loss of range, and tighter couplings increased interference without compensating increase in range.

A set of interference curves constructed on the principle of Fig. 7(c) or Fig. 7(d) will give us some idea of the

is stated in the Madrid Regulations, but as mobile stations have the right to work on any frequency within their band it is only possible for the Regulations to lay down the permissible variation during a transmission.

The sources of error in frequency during a transmission can be traced to three main causes. (a) The slow and progressive alteration of frequency due to changes in temperature. (b) Fluctuations of frequency, due to fluctuation of filament supply voltage. (c) Change of aerial capacitance, and to some small extent change of insulation resistance, due to weather.

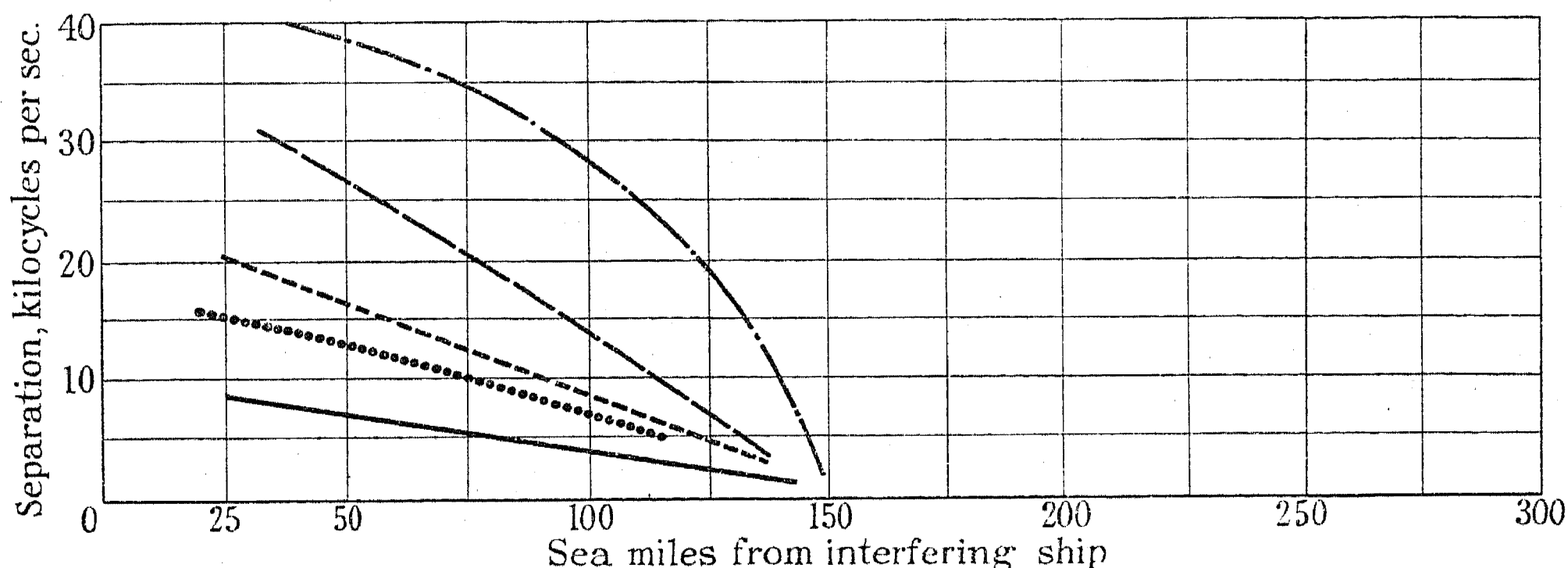


FIG. 7(d).—Derived interference curve, showing position between transmitters of different types for equality of signal and interference for different separations.

— 10 per cent coupling.
 - - - 5 per cent coupling.
 . . . 2 per cent coupling.
 - . - Q.G.
 — I.C.W.

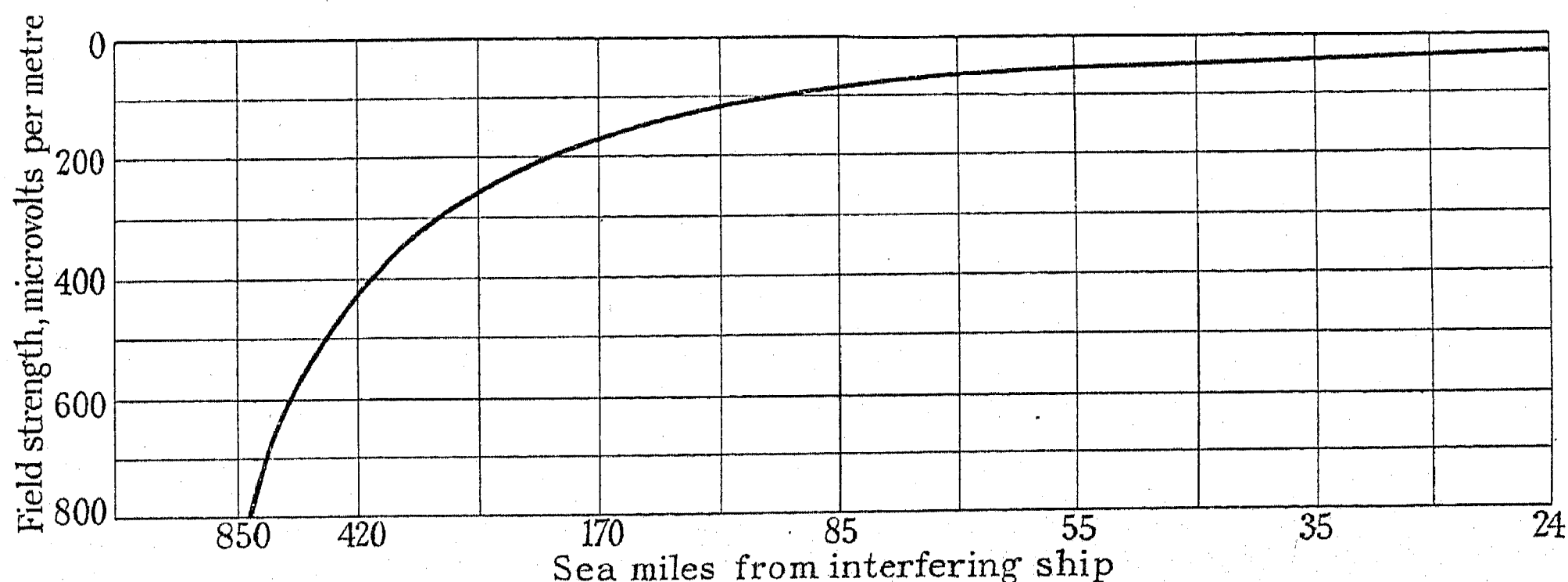


FIG. 7(e).—Mean night field-strength per 20 watts radiated, at 500 kilocycles per sec.

improvement to be hoped for as main spark transmitters gradually die away and as the selectivity of receivers is gradually increased. It will also give us an idea of the nature of the problem, which will then have to be faced, of obtaining immediate communication on the International Distress and Calling Wave (500 kilocycles per sec.).

This completes the study of interference due to the natural spread of the emission, assumed to be tuned to the intended frequency.

Interference due to Valve Transmitters.

It is also necessary to consider the question of interference likely to be caused by valve transmitters working off the intended frequency. The permissible tolerance

Of these, (a) can be measured in a test room, and can be reduced to the requisite figure by suitable construction. Any kind of oscillator which is not provided with some form of thermostatic control is just as liable to this trouble as any other kind. Indeed, the larger and more robust the construction of the oscillator the slower and the steadier is this progressive alteration likely to be. Other kinds of oscillation-frequency controllers, such as tuning forks and crystals, are subject to some extent to temperature variation. Automatically-compensated circuits, and modern crystals, show very small variations of frequency due to temperature-change.

Repeated observations show that there is very little difference between the rate of slow drift of a transmitter as measured in a test room, and the performance of the

transmitter at sea. In almost all cases, if a transmitter is started from cold the rate of drift for the first 10 minutes will be about double the subsequent rate. The initial comparatively rapid drift can be avoided by switching on the valve filaments, or by using other means of warming up, before transmission begins.

Errors due to (b) can be kept within bounds by compensating devices in the wireless a.c. circuits, or by heating the filament from batteries. Such errors should not exist to any appreciable extent in modern apparatus. There remains the possibility of the voltage of the ship's d.c. supply dropping appreciably under the added wireless load, but this can only occur in the most ancient vessels. The expression "appreciable extent" is intended to mean any alteration of frequency which can cause annoyance to the receiving telegraphist due to material change in the beat note.

Changes due to (c) can only have effect if the aerial is directly connected to the oscillator, or is very tightly coupled to it. Experiments have recently been carried out to determine the probable quick variation in frequency due to these causes, and the results show that from the point of view of marine communications these changes are truly negligible.

Three methods of measuring these changes have been employed, each designed to suit particular circumstances. For frequencies in the band of 110 to 160 kilocycles per sec., signals have been watched with a steady local oscillator, the beat note being set to a very low pitch. Any material quick fluctuation in frequency is at once apparent. For frequencies in the band of 365 to 515 kilocycles per sec., in which careful observation of received C.W. signals is difficult owing to interference of all sorts, observations have been made in individual ships when at sea and clear of severe interference by exciting the aerial at its own frequency by means of a receiving valve used as an oscillator, and listening to the beat note in the ship on a receiver without any external connections. For frequencies above 8 000 kilocycles per sec., the Post Office have kept watch on special programmes transmitted from ships at sea. The figures obtained from these tests are given in Table 2. Except in the G.P.O. tests precise measurements were not obtained; but since the beat note was in all cases set at about 250 cycles per sec. a change of, say, 100 cycles per sec. was most obvious.

These figures are not surprising when it is considered that the only material change in aerial capacitance is that due to the part of it in proximity to the funnel, or to something similar. It must also be remembered that if the feeder sways away from the funnel it very likely sways nearer to something else. Fig. 8 shows the capacitance, calculated according to Prof. Howe's formula, for a 10-metre run of feeder at different distances from the funnel. The two sizes of wire quoted are those most common in the British mercantile marine.

From the above it appears that the greatest practical difficulty likely to be experienced in the organization of marine communications when the use of valve transmitters becomes general will be the difficulty of setting the oscillator exactly to any predetermined frequency. This is equally true of any form of oscillator, or even of a wavemeter. It is all a question of good mechanical

TABLE 2.

Conditions of observation								Estimated variation in frequency (cycles per sec.)	
Method of observation	Type of ship	Position of feeder	Approximate capacitance of aerial alone	Approximate frequency	Weather	Motion of ship	Aerial normally taut	Aerial slack	
A*	Small cargo steamer ..	Far away from funnel	$\mu\mu\text{F}$ 444	kilocycles per sec. 500	Good	Nil	Not appreciable	Not appreciable	
					Fair	Pitching moderately	75	150	
					Fair	Rolling moderately	100	200	
					Bad	Rolling heavily	125	250	
A*	Small cargo steamer ..	Average 10 metres	555	500	Fair	Rolling slightly	200	250	
					Bad	Rolling heavily	300	400	
					Fair	Slight	Cannot be noticed		
B†	Large vessels ..	20 metres	777	140	Bad	Rolling a little	Cannot be noticed		
					Fair	Slight	{ Rapid changes of frequency due to movement of aerial: too small to be noticed		
C‡	Large vessel ..	—	—	8 000	Bad	Rolling a little			

* Method A.—Test by oscillation of ship's aerial with a receiving valve, and observing fluctuations of beat-note on ship's receiver.
† Method B.—Test by listening to signals from a distant ship, and observing fluctuations of beat-note when using a known steady local oscillator.
‡ Method C.—Test by listening to signals from a distant ship, and observing fluctuations of beat-note when using a known steady local oscillator.

construction and open scales free from parallax. It is not difficult to reduce the frequency error to some figure not exceeding 0.05 per cent with modern apparatus. At frequencies above 10 000 kilocycles per sec. the error may rise to 0.1 per cent. There still exist a small number of less well-made transmitters in which this error is greater.

The necessary conditions for immediate communication when using a predetermined frequency of very narrow spectrum, and receivers of very sharp discrimination, are difficult to attain. Before such a basis of communication can be reliable all receivers must be susceptible of sufficiently accurate adjustment, and it must be certain that they will not slip from the correct adjustment on account of vibration. The problem of realizing the ideal is far

effect of a continuous-wave emission, or of the unmodulated component of a carrier wave, when beating with the Type A₂ or Type B waves which are generally used for direction-finding. The troubles due to very weak heterodyne interference are divisible into two separate parts, (a) the introduction of a definite error, and (b) the difficulty in observing, owing to a change in the quality of signals on the two sides of the arc of extinction. A small number of reports have been received referring to both these matters. It appears that with regard to (a) a great deal depends upon the details of the instruments and the relative strengths of the interference and the wanted signal.

An account of the principles which should govern the

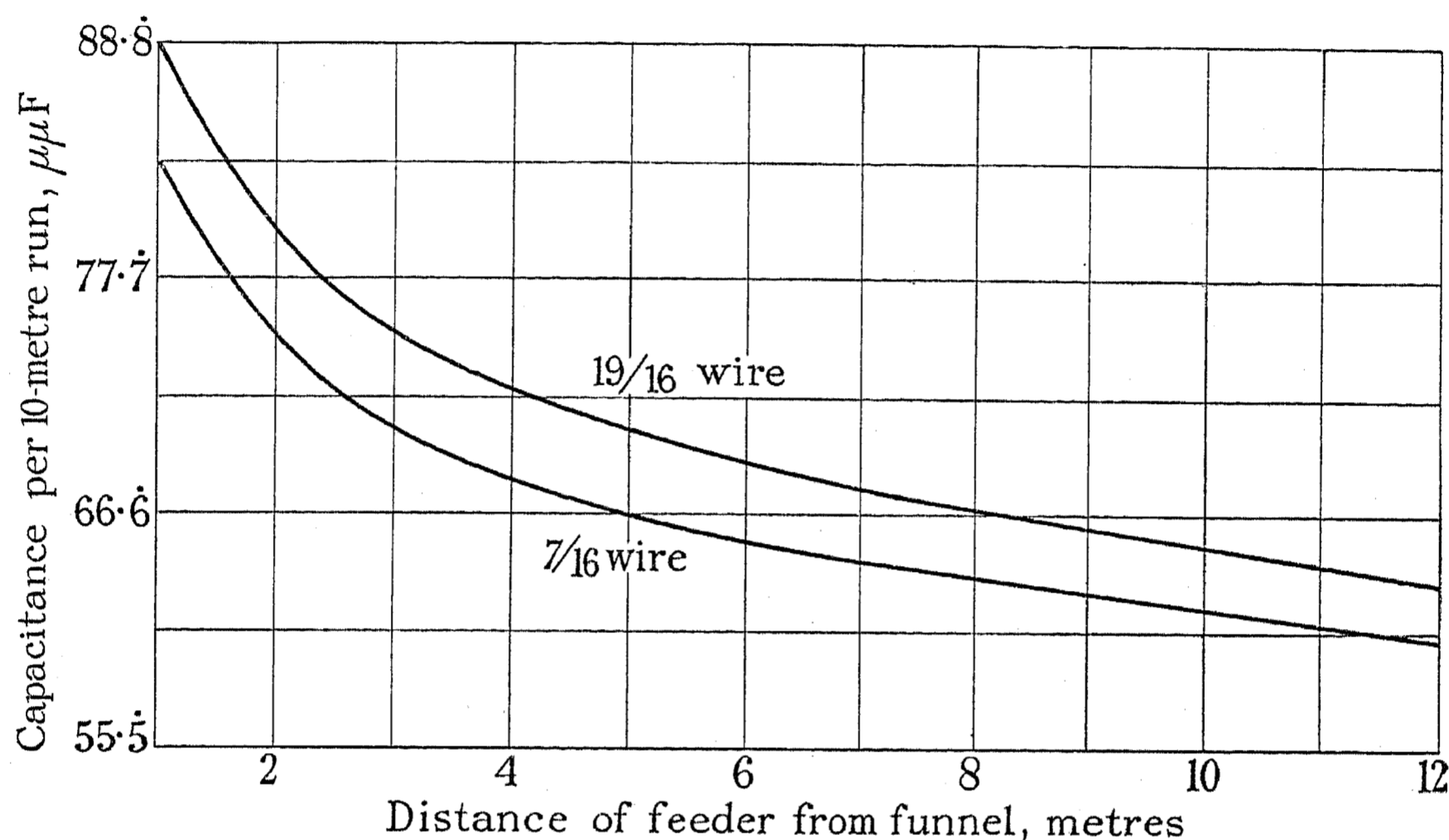


FIG. 8.—Calculated capacitance per 10-metre run of feeder (single-wire, assumed parallel to funnel).

more difficult with respect to receivers than with respect to transmitters.

(4) INTERFERENCE WITH DIRECTION-FINDING.

The question of interference with direction-finding divides itself into two distinct sections; namely interference due to a high noise level, and heterodyne interference. A high noise level may be due to the ship's electrical machinery or to outside signals. A correct choice of site for the direction-finder will reduce the noise level to a reasonable figure, but in many cases the use of the maximum amplification of which most modern direction-finders are capable may bring the noise level up to audibility. In such a case the operator must choose between maximum amplification and a noisy background, or reduced amplification and a silent background. This form of interference is not very serious if it is approximately equal on all bearings, but if it is unequal it causes great inconvenience and is therefore an indirect cause of error. High noise level due to outside signals is dealt with later with special reference to morse interference. The principles used in that examination also apply so far as audible speech or music are concerned, though it is difficult to reach any fair idea of numerical values on account of the constantly changing value of the modulation.

The true heterodyne interference consists of the

matter will now be given. In Fig. 9 suppose OB is the direction of the beacon whose bearing is required, and OI that of the interfering source. Also suppose that SOZ represents the silent zone of the beacon signal under any particular working conditions. Then when the search coil of the goniometer (or the swinging coil) is turned to one side of the silent zone, say to the line OZ, the effect of the interference will be in some direct proportion to $\epsilon \sin(\beta - \alpha)$, ϵ being the field strength of the interfering station. Similarly when the search coil is turned to the position OS the interfering effect will be in direct proportion to $\epsilon \sin(\beta + \alpha)$.

Now if one of these is nearly zero and the other has some appreciable value, there will be a source of possible error. If the heterodyne interference is strong enough to cause the note of the wanted signal to break, the operator will at least have warning that the bearing should be regarded with suspicion; but reports have been received indicating that errors have been observed when the strength of the heterodyne interference has not been great enough to break the note. In this case an error is introduced of which the operator has no warning.

It is well established that the effect of a heterodyne beat is to cause a considerable reduction in the width of the arc of silence, and if this effect is present at one side of the swing and absent at the other the result will be to distort the bearing in such a way

as to make it appear that the beacon is more nearly in the same direction as the interfering station than is the fact.

It is very difficult to determine from the reports available the values for the interfering field, and the frequency separation between the interference and the wanted signal, which will cause a definite error. Very careful laboratory experiments have failed to produce any consistent results. With some types of instruments, errors in bearing as large as 2° have been produced artificially; with others it has been impossible to produce any errors which are worthy of notice from the navigational point of view.

The effect of interference is quite obvious. It is very

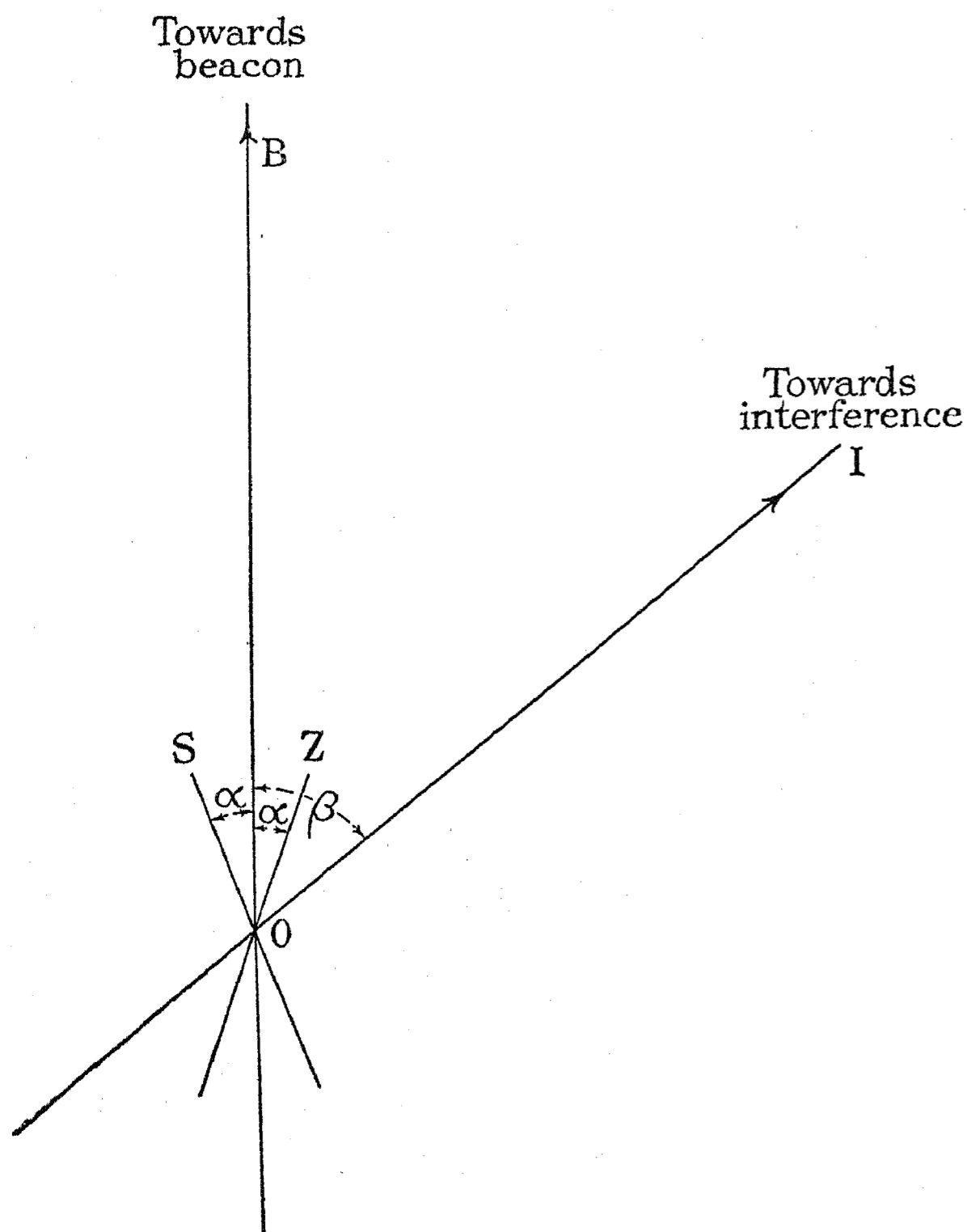


FIG. 9.

easy to produce artificially conditions which will cause a marked difference in the quality of the sound of the signal at the two points of extinction, and with unskilful observers this might cause errors, but good observers are not likely to be deceived.

The effect of strong heterodyne interference is quite different. When the strength of the interfering field is comparable with that of the wanted field the injected voltage will be sufficient to give an approximately equal beat effect on both sides of the arc of silence (except when β is very nearly equal to α), and so far laboratory experiments indicate that no error will be introduced. In addition to the effect of the Type A_1 interference on the wanted signal, the latter also heterodynes the interference, which would otherwise be audible; but this only means that it is possible to get a bearing of the interfering station without the use of a local oscillation generator. This effect is not produced if the separation

is much in excess of 3 kilocycles per sec., and therefore this matter has no great practical importance.

The analysis of interference with direction-finding, due to telegraphy, has been tackled from the point of view of noise level in the following way. As the object has been to study the probable result from the point of view of ships at sea, the observations and data used have been collected from reports by telegraphists in ships. They therefore cannot be regarded as quantitative measurements, but only as comparisons. An examination of the average of these observations, however, shows remarkably good concordance. The chief solid point of reference was that the majority of British beacons had been regulated so that they gave a field strength of 50 microvolts per metre at their nominal working range. From this figure the approximate field strength at various distances can be derived. The second point is that in taking directions practically all telegraphists note the point of extinction of signals, and therefore the field strength of the beacon at any distance multiplied by the sine of half the angle of silence will give the field strength which will just not produce an audible signal. The hearing of most telegraphists can be regarded as equally acute, and there is close similarity in the performance of various instruments of any particular type; so, continuing to work by averages, the figures thus obtained will bear some close relation to the average truth. It has been established in the past that direction-finding loops of reasonable shape do in fact under seagoing conditions show an effective height which is proportional to their area, and in the case of frames the effective height is proportional to the area multiplied by the number of turns. The gain of the amplifier is fairly accurately known, at any rate in cases where reaction is not used. Therefore if we multiply together the field strength, the sine of half the angle of silence, the effective height of the loop, and the gain of the amplifier, we ought to arrive at a figure whose value is constant.

This has been done in a simplified form for several types of direction-finders. All of these types are built on the Bellini-Tosi principle, but as all have similar field coils and search coils it has been possible to ignore the additional term covering the coupling between the field coil and search coil. When obtaining similar figures for direction-finders of the rotating-frame type this term should be remembered. If its value for the common untuned Bellini-Tosi system is regarded as unity, its value for an untuned directly-connected swinging loop will be about $1\frac{1}{2}$, and for a directly-connected tuned swinging loop it will be about $2\frac{1}{2}$. If this factor, whatever its true value may be, is regarded as being included in the figure used as the "total voltage gain" (which includes low-frequency amplification), the figures for all types of instruments appear to be comparable.

For the sake of simplicity, the factors selected have been the following: A = area of loop, in square feet; T = number of turns; G = total voltage gain of amplifier; α = half the angle of silence, in degrees; ϵ = field strength, in microvolts per metre. Then, if the observations and principles are reliable, the value of the expression $ATG\epsilon \sin \alpha$ should be the same, or nearly the same, for all types of direction-finders examined.

A sufficient number of reports have been received to

TABLE 3.
Performance Details of Various Types of Direction-Finding Installations.

Refer- ence letter	Date of installa- tion	Loop		Total gain (volts) of amplifier	ATG	Average down to $\epsilon = 50$		ϵ (microvolts per metre) Distance (miles)	220 25	125 50	74 75	50 100	27 150	16 200
		Area, sq. ft.	Turns			$\epsilon \sin \alpha$	ATG $\epsilon \sin \alpha$							
A	1918	200	1	50	10	30.6	306	Av. swing ($= 2\alpha$)	17.5	32	41	60	—	—
								$\sin \alpha$	0.153	0.276	0.35	0.5	—	—
								$\epsilon \sin \alpha$	33.5	34	26	25	—	—
B	1925	{ 24 12	{ 5 10	115	14	19.4	270	Av. swing ($= 2\alpha$)	10	21	27	43	—	—
								$\sin \alpha$	0.087	0.18	0.23	0.36	—	—
								$\epsilon \sin \alpha$	19	22.5	18	18	—	—
C	1927	12	10	200	24	13.4	320	Av. swing ($= 2\alpha$)	7	14	20.5	29	50	60
								$\sin \alpha$	0.06	0.122	0.177	0.248	0.42	0.5
								$\epsilon \sin \alpha$	13	15	13	12.5	11	8
D	1931	7	8	400	22	14	315	Av. swing ($= 2\alpha$)	6	15	23	30	33	38
								$\sin \alpha$	0.05	0.13	0.199	0.26	0.284	0.325
								$\epsilon \sin \alpha$	11	16	15	13	7.5	5.2
E	1933	7	8	750	42	7.5	325	Av. swing ($= 2\alpha$)	4	8	—	12	—	—
								$\sin \alpha$	0.035	0.07	—	0.1	—	—
								$\epsilon \sin \alpha$	7.8	9	—	5	—	—
F	{ Same as E, worked at full possible amplification }			2 500	140	2.1	294	Av. swing ($= 2\alpha$)	1.25	2	—	4	8	12
								$\sin \alpha$	0.01	0.017	—	0.035	0.07	0.1
								$\epsilon \sin \alpha$	2.2	2.4	—	1.8	1.9	1.6

allow reasonable averages to be obtained from five different combinations of instruments, ranging from 10-year old installations to those of to-day. The average values of the product $ATG\epsilon \sin \alpha$ for these five

as the saturation of the amplifier, the probability of an imperfect cosine diagram, the mental effort of taking bearings through interference, etc., the value of $\epsilon \sin \alpha$ ought to be a constant for any particular installation.

TABLE 4.
Permissible Maximum Values of Interfering Field, Expressed as Percentages of Wanted Field.

	$\alpha = 2^\circ$	3°	4°	5°	6°	7°	8°	9°	10°	15°	20°	30°
$\beta = 90^\circ$	0.034	0.05	0.07	0.087	0.1	0.12	0.14	0.15	0.175	0.27	0.36	0.57
$\beta = 60^\circ$	0.04	0.06	0.08	0.1	0.11	0.13	0.15	0.17	0.18	0.27	0.34	0.5
$\beta = 45^\circ$	0.067	0.1	0.12	0.13	0.15	0.18	0.19	0.2	0.21	0.3	0.38	0.52
$\beta = 30^\circ$	0.09	0.13	0.18	0.18	0.2	0.23	0.24	0.26	0.27	0.37	0.45	0.59

types are 306, 270, 320, 267, and 310. Taking into consideration the conditions under which the observations were made, it is considered that this agreement is sufficiently good to justify further examination along these lines. The details of the observations are shown in Table 3.

Now if there were no inconsistencies due to such causes

This value has been plotted in Fig. 10, which shows that it is not constant but that the curves are fairly similar in form.

The comparatively low value of $\epsilon \sin \alpha$ when the field is very strong may be partly due to the fact that under these conditions the ratio of signal strength to noise level is good. We know by experience that when this is

TABLE 5.
Permissible Strength of Interfering Field for "100 Mile"

Reference letter of installation										A		B			
Distance, nautical miles															
Field of beacon, microvolts per metre ..										220		125		50	
Average value of α , degrees										8		16		30	
Proportion strength of interfering field bears to wanted field ($\beta = 90^\circ$)										0		0		0	
										0		0		0	
										2		2		2	
										4		4		4	
										6		6		6	
										8		8		8	
										10		10		10	
Real strength of interfering field ($\beta = 90^\circ$)										0		0		0	
										3		3		3	
										6		6		6	
										6		6		6	
Nominal range of beacon, nautical miles										200		100		50	
Probable distance (nautical miles) at which reliable bearings can be taken by a good observer at the stated nominal range over sea:—										150		75		40	
Day										150		75		40	
Night										150		75		40	

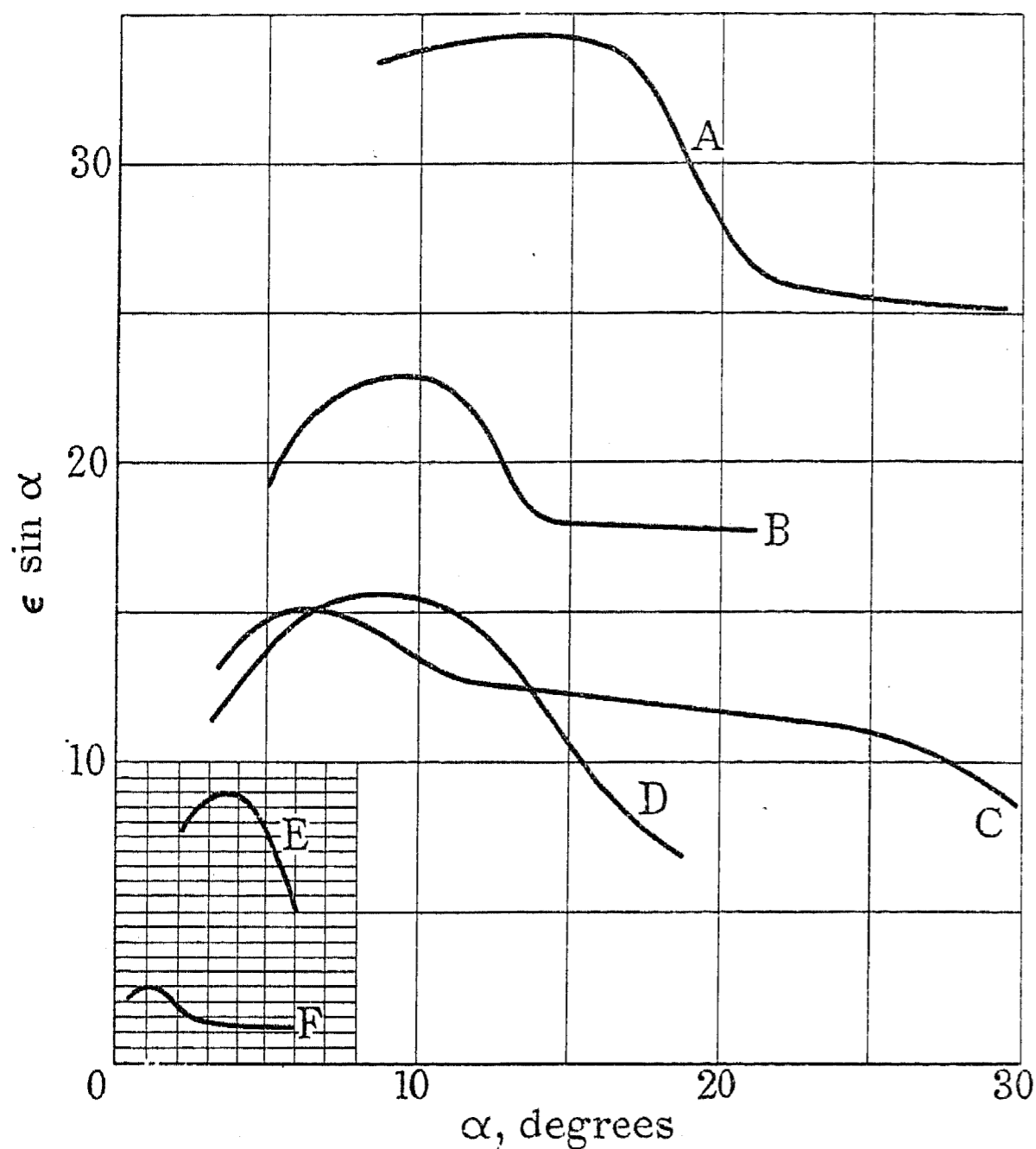


FIG. 10.

the case most telegraphists will work to the true point of extinction, but that when this ratio is bad, i.e. when

signals are weak, most men prefer to work to points at which signals are just audible. Under these conditions the angle of swing must vary from hour to hour, and is larger than the swing between points of complete extinction.

Working onwards from this point, we arrive at an approximate figure for the field strength of an interfering signal which will just leave the background silent through the arc of silence of the wanted signal. If we call half the arc of silence α , as before, and the difference in bearing between the wanted and interfering stations β (see Fig. 9), we see that at the point of extinction of the wanted signal the voltage injected to the amplifier is in proportion to $\epsilon_A \sin \alpha$, the voltage injected by the interfering station being $\epsilon_B \sin (\beta + \alpha)$ on one side and $\epsilon_B \sin (\beta - \alpha)$ on the other. Assuming the frequencies of the wanted and unwanted signals to be the same, we can at once obtain the maximum permissible value of the interfering field for any given strength of wanted signal.

Such values are plotted in Fig. 11, which brings out two points. In the first place the permissible maximum value of the interfering field does not appear as a percentage of the wanted field, but is much more nearly a constant for any particular type of installation; and secondly we see that, within reasonable limits, the wider the angle of silence the stronger the permissible interfering field. It is a common practice among telegraphists to reduce amplification, and so widen the arc of extinction, when it is necessary to work through severe interference.

TABLE 5—continued.

Beacons to Make a Silent Background Possible.

C					D					E					F				
		25	50	100			25	50	100			25	50	100			25	50	100
		220	125	50			220	125	50			220	125	50			220	125	50
		3.5	7	15			3	7.5	15			2	4	6			0.62	1	2
Decibels down	Volts ratio				Decibels down	Volts ratio				Decibels down	Volts ratio				Decibels down	Volts ratio			
0	1	0.06	0.12	0.36	0	1	0.05	0.13	0.26	0	1	0.034	0.07	0.1	0	1	0.01	0.017	0.035
6	2	0.12	0.24	0.52	8	2.5	0.12	0.311	0.65	8	2.5	0.085	0.12	0.25	10	3	0.03	0.05	0.1
12	4	0.24	0.48	1.4	16	6	0.3	0.8	1.56	16	6	0.2	0.72	1.5	20	10	0.1	0.17	0.35
18	8	0.48	0.96	2.8	24	16	0.8	2.1	4.3	24	16	0.54	0.11	1.6	30	32	0.32	0.56	1.1
24	16	0.96	1.9	5.6	32	40	2	5.4	10.4	32	40	1.3	2.8	4	40	100	1	1.7	3.5
30	32	1.9	3.8	11.2	40	100	5	13.6	26	40	100	3.4	7	10	50	300	3	5	10
0	1	μV per metre			0	1	μV per metre			0	1	μV per metre			0	1	μV per metre		
9	3	13	15	13	12	4	11	17	13	12	4	7.5	8.5	5	15	6	2.2	2.1	1.6
18	8	40	45	43	24	16	44	71	56	24	16	30	34	20	30	32	13	14	10
		106	120	140			175	260	215			120	134	80			70	65	50
		200	100	50			200	100	50								200	100	50
		200	150	75			300	175	100	Anything up to the figures shown under F							600	450	300
		300	150	75			400	200	100								1 000	600	400

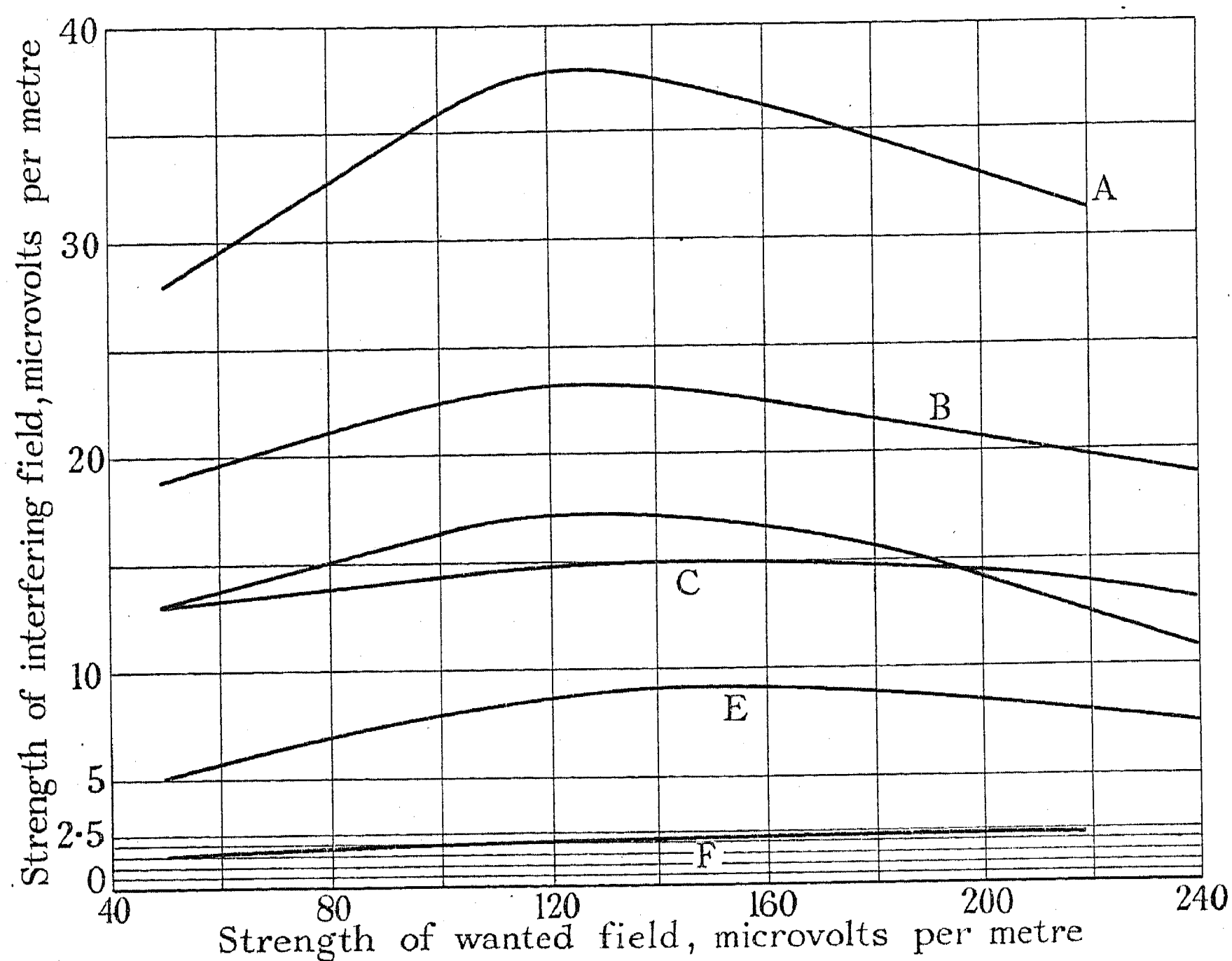


FIG. 11.—Permissible strength of interfering field at zero separation. $\beta = 90^\circ$.

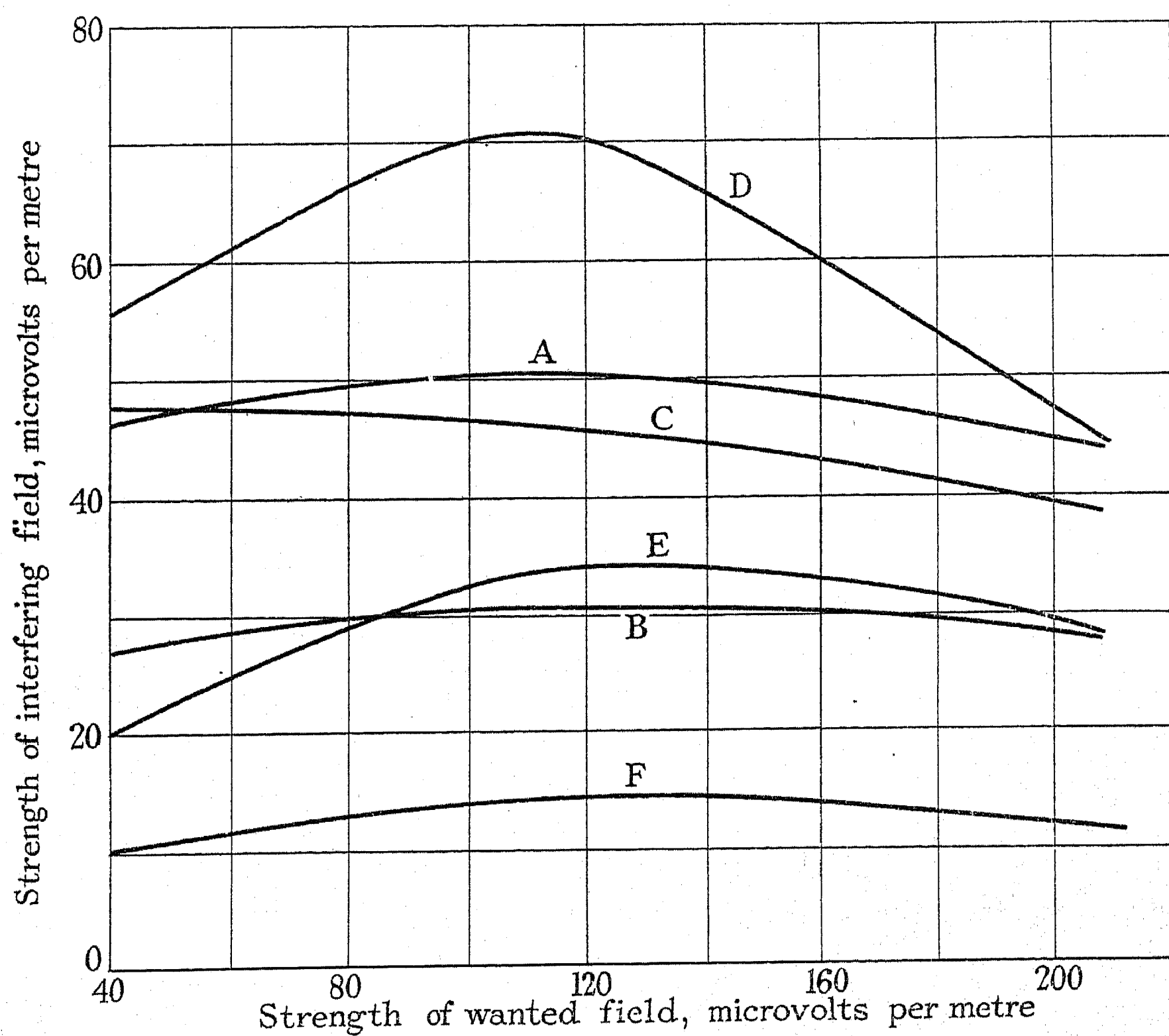


FIG. 12.—Permissible strength of interfering field at 3 kilocycles per sec. separation. $\beta = 90^\circ$.

TABLE 6.*
Interference between Beacons.

	Time-group 1	Time-group 2	Time-group 3
A with A, 15 μ V per metre 5 B with A, 50 C with A, 150	Nil Ailly with Cromer Cromer with Ailly Nil Nil	Nil Nil Ouessant with Daunts† Nil	Omo-Korsor-Nyborg Flamborough with Geitunger Nil Nil
B with B, 15 μ V per metre 5 A with B, 50 C with B, 50	Nil Nil Nil La Hague with Round Island	Nil Nil Nil Nil	Nil Nil Nil Nil
C with C, 15 μ V per metre 5 B with C, 50 A with C, 150 E with C, 150	Nil La Hague with East Goodwin Round Island with La Hague Nil Nil	Nil Torungen with Horns Reef Horns Reef with Torungen Nil Nil Nil	Nil N. Foreland with Gatteville Gatteville with N. Foreland Nil Nil Nil
E with E, 15 μ V per metre 5 F with E, 50 C with E, 150 G with E, 150	Nil Nil Dungeness with Ostend† Nil Nil	Nil Nil Nil Nil Nil	Nil Barra with Roker Pier Nil Nil Nil
F with F, 15 μ V per metre 5 E with F, 50 G with F, 50 H with F, 150	Nil Dungeness with Rame Dungeness with Haaks Nil Orford with Dungeness Orford with Haaks Nil	Nil Terschelling Bank with Boulogne Nil Orford with Terschelling Bank Norderney with Terschelling Bank	Nil Nil Nil Nil Nil
G with G, 15 μ V per metre 5 F with G, 50 H with G, 50 E with G, 150 J with G, 150	Nil Orford with Shambles Dungeness with Orford Hirschholm with Faerder Roches Douvres with Shambles Nil Nil	Nil Orford with Cherbourg Terschelling with Orford Start with Cherbourg Sandettie with Orford Nil Nil	Nil Nil Nil Nil Nil Nil
H with H, 15 μ V per metre 5 G with H, 50 J with H, 50 F with H, 150 K with H, 150	Nil Nil Shambles with Roches Douvres* Orford with Dyck Faerder with Hirschholm Nil Nil Nil	Nil Sandettie with Start* Start with Sandettie Cherbourg with Start Orford with Sandettie Nil Nil Nil	Nil Casquets with Ruytingen Nil Nil Nil Nil
J with J, 15 μ V per metre 5 H with J, 50 K with J, 50 G with J, 150	Nil Nil Nil Nil Nil	Nil Nil Nil Nil Nil	Nil Nil Casquets with Seint†† Nil Nil
K with K, 15 μ V per metre 5 J with K, 50 H with K, 50	Nil Nil Nil Nil	Nil Nil Nil Nil	Nil Nil Nil Nil

* Derived from Fig. 13.

† Very slight.

‡ Not important for navigation.

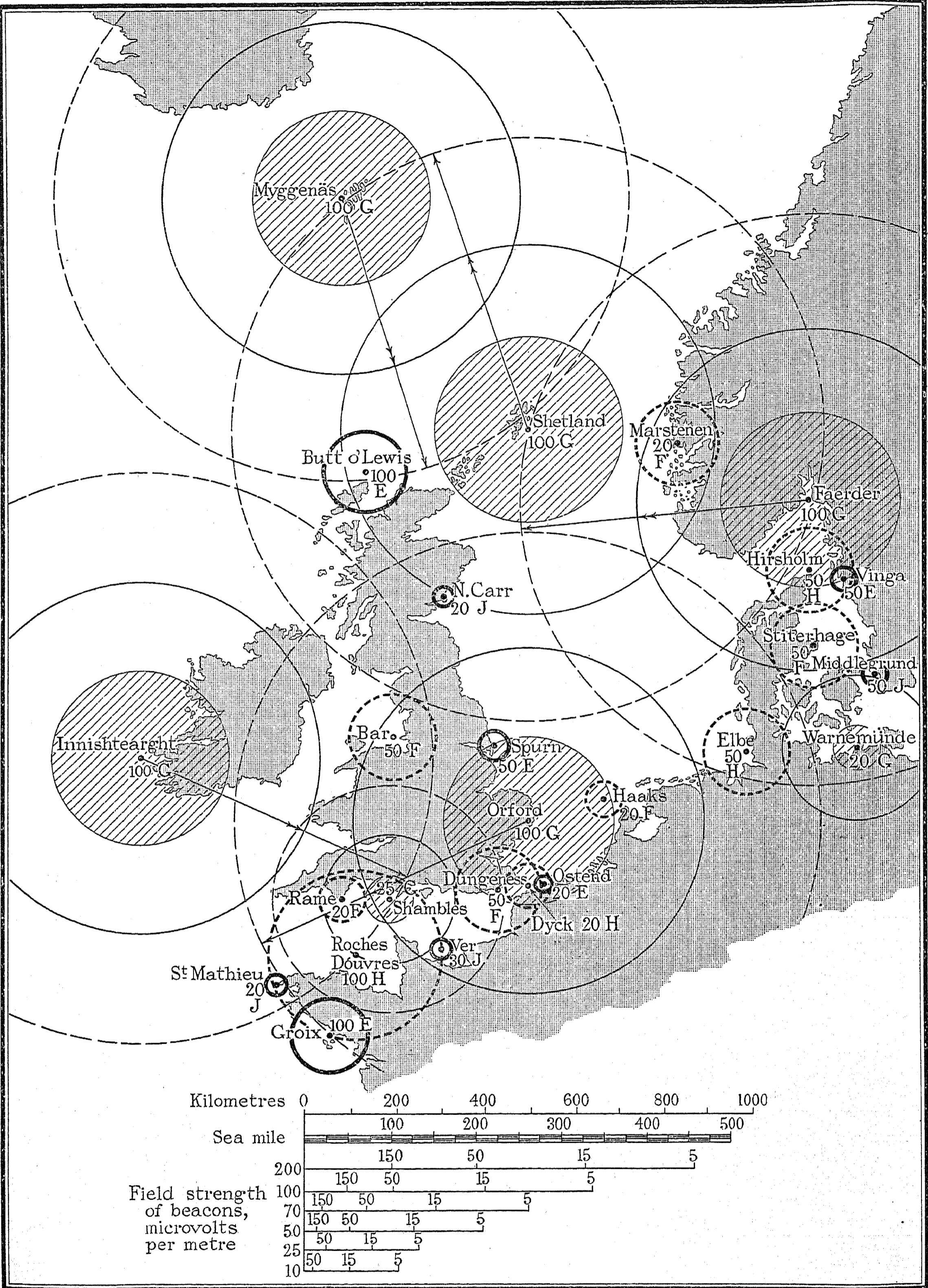


FIG. 13.—Time-group 1, G wave. Probable interference: F with G, Dungeness/Orford; H with G, Roches Douvres/Shambles and Hirschholm/Faerder; G with G (field 5 microvolts per metre), Orford/Shambles. Working areas are cross-hatched. Letters indicate frequencies; numerals indicate working ranges.

It is also clear that from the point of view of heterodyne interference the reverse is the case. The narrower the arc of silence, the less the possibility of errors being introduced from this cause.

In Table 4 the permissible maximum values of the interfering field, expressed as percentages of the wanted field, are shown for several values of α and β .

If the response curve of the amplifiers forming part of the various installations is applied to the foregoing figures, the permissible field strength of interfering signals on frequencies other than that of the wanted signal can be arrived at. Some of these results have been tabulated in Table 5, and the results for 3 kilocycles per sec. separation are shown in Fig. 12. All these figures have been collected from instruments of a particular type, but it has also been possible to compare them with the data obtained from the single-frame type of direction-finder. The comparable figures derived from these data are inserted under "F" in Table 5.

Putting all these figures together, and remembering that there are still many hundreds of the older instruments in service, it has been possible to work out the probable mutual interference between the radio beacons off the north-western coast of Europe. These have recently been reorganized, making use of Type A₂ waves, and the result of examining this organization on the foregoing lines is shown in Table 6.

In order to carry out the examination a rough map was prepared of the waters in question. Over this was laid a sheet giving all the names and positions of one of the groups of beacons which transmit simultaneously. There are three such groups. Over this pair was laid a third sheet giving those beacons in the group in question which transmit on one of the selected frequencies. Eight definite frequencies have been selected in the beacon band, the frequency separation being 3 kilocycles per sec. The working areas, that is to say the areas in which the field strength exceeds 50 microvolts per metre, are shaded, and circles showing the interference zones have been drawn around them. These zones have been plotted for field strengths of 15 and 5 microvolts per metre respectively. Thus far we can arrive at the probable mutual interference on the wave in question.

The interference circles of beacons in this group working on the two neighbouring frequencies are plotted in thick broken lines, the circles representing a field of 50 microvolts per metre. The interference circles of beacons working on the next frequency, but one on each side, are plotted in thick continuous lines, the circles representing a field of 150 microvolts per metre (see Fig. 13). The extent to which these circles overlap into the shaded areas gives the probable interference. A set of 24 of these diagrams is necessary to complete this study; the result is collected in Table 6.

The permissible strength of the interfering fields has been selected on the basis of a difference of bearing (β) of 90 degrees, and it is obvious that in many cases this angle is much less. Also in many instances a considerable mass of land intervenes between the interfering station and the working area. In this case the strength of the interfering field will often be less than half that indicated. There are also a great many cases where bearings would not be absolutely necessary in the "interfered" areas.

In addition to the above, the note frequency used by the beacons is carefully organized so as to give the greatest possible difference in note in cases where interference is probable from the point of view of high-frequency tuning.

Taking all the above into consideration it may safely be assumed that the mutual interference between beacons as at present organized will in actual practice be zero.

In conclusion, the author wishes to express his gratitude for the assistance which has been extended to him during the preparation of this paper.

His thanks are particularly due to Mr. Jean Marique, of the Société Anonyme International de Télégraphie sans Fil, Belgium; to Mr. W. G. Kuyck, of Radio-Holland; and to the technical manager of the Marconi International Marine Communication Co., and his staff. He is also grateful to the administrative staff of the same Company; and to the numerous telegraphists at sea from whose clear and straightforward reports much of the large quantity of data necessary for the preparation of this paper has been collected.

DISCUSSION BEFORE THE WIRELESS SECTION, 2ND MAY, 1934.

Mr. M. Reed: I think that those of us who are engaged in the design of wireless apparatus for the mercantile marine should be particularly grateful to the author for a paper which puts on a quantitative basis a subject which has hitherto been investigated mainly by qualitative methods. The data given in the paper should be of considerable assistance to the designer, who has been somewhat handicapped, in the past, by having to rely on the reports of aural observers; particularly in those cases where the number of different opinions which he has received has been exactly equal to the number of listeners!

The author, when discussing the interference caused by broadcasting stations, does not mention the demodulation effect which such stations may introduce at the input to the detector valve. The desired C.W. signal

combined with the output of the local oscillator represents approximately a modulated signal and, as in the case of ordinary broadcast reception, the carrier of the interfering station should cause some reduction in the signal output. For example, one would expect in the case of a station such as Brasov, where the interfering station may be many times stronger than the desired station, that the demodulation effect would be sufficiently appreciable to make the results obtained in practice worse than a study confined to the resonance curve of Fig. 1 would indicate.

I think that probably the only solution of the interference problem on the 110- to 160-kilocycle band is to use two, and if possible three, tuned high-frequency stages. The use of note filters may help matters, but the note filter has the disadvantage that its selectivity

is governed by the stability of the transmitting station. In the case of a note filter tuned, say, to 1 000 cycles per sec., a difference of 100 cycles per sec. will introduce an appreciable reduction in signal output, yet a frequency drift of this order can frequently be expected with the type of marine transmitter used on the long wave band.

With regard to the response curve shown in Fig. 1, can the author give some particulars of the type of receiver which he has in mind? If one considers that 10 kilocycles at 160 kilocycles per sec. corresponds to a mistuning of about 6 per cent, and that 10 kilocycles at 600 kilocycles per sec. corresponds to about 2 per cent, the selectivity of the receiver represented by the curve in Fig. 1 is, if anything, somewhat inferior to that of the receiver whose curve is given in Fig. 3. It would also be of interest to know what type of receiver is represented by Fig. 3. As far as I know, most ship receivers have one tuned circuit, in which case the selectivity values given by Fig. 3 seem rather higher than one would expect.

Table 2 is of great interest. I have made a number of tests on standard transmitters of the self-exciting type with the aerial directly connected to the oscillator, and I have found that the frequency drift is well within the tolerances laid down by the Madrid regulations. It would be of interest to know whether the values to which the author refers were obtained with a similar type of transmitter.

With regard to the problem—raised on the same page—of setting the oscillator to a given frequency, the difficulty seems to me mainly an economic one. To obtain the tolerances required it is not difficult, up to 500 kilocycles per sec. at any rate, to design a wavemeter whose scale can be read with sufficient accuracy; the question is rather whether the expense entailed in supplying such a wavemeter to each ship can be justified.

On page 370 the author shows that, when working with stations at the same strength, the product $ATG \sin \alpha$ is approximately constant for a number of receivers manufactured during the past ten years. Now, of these four quantities, A , T , and G , are constants for the given receiver, but α , in the case of a receiver installed on a ship, depends somewhat on the value of the ship's rotating field. In practice this field is more or less compensated by the use of a semicircular corrector. Has the author taken this factor into consideration and, if so, can we assume that the efficiency of the semicircular corrector has been the same throughout for all the receivers which have been investigated?

Mr. F. Woods: There are one or two points with regard to Section (4) on which I would invite the author's opinion and comments. All forms of interference are bad, but in my opinion interference can be very much worse in the case of direction-finding, first because it tends to make direction-finders unreliable through no fault of their own, and secondly because it discredits an art which is working hard to establish its claim as a reliable aid to the navigation of ships. I should like to suggest that very much greater prominence should be given to the problem of noise level, particularly that resulting from electrical machinery on the ship itself. Inductive interference is probably the oldest difficulty in the history of direction-finding, and I think we should

watch very closely the increasing use of small frames with high-efficiency receivers, particularly where such frames are secured directly to the deck. The author's point about correct choice of site is not a particularly easy proposition, in view of the numerous considerations which have to be taken into account. For example, the best position for an aerial is usually in the neighbourhood of the bridge structure, but here a good deal of important wiring finds its home, and almost invariably the interference due to noise level is very much worse in this part of the ship than elsewhere. It is these conductors which pump energy into the frame with the directional effects noted by the author, and these effects are definitely a prolific source of errors.

Modern receivers are sufficiently well screened to take care of themselves, so that putting the frame out of harm's way seems to be the only solution to this particular problem. Ideally one is committed to a centre-line fitting, and in such cases the amount of available shift for the frame is rarely sufficient to make any appreciable difference so far as inductive pick-up is concerned. It has been observed experimentally that these inductive or interfering fields are particularly low-lying, and also that raising the frame vertically, even a very few feet, may make all the difference between impossible reception conditions and a perfectly silent background. This question of frame elevation in connection with shipboard interference is, I submit, a very real solution of the problem of interference.

Once immune from the troubles of irregular background, we are in a position to tackle what I consider to be the less of the two evils, namely heterodyne interference, more popularly known as fringe jamming. This is probably more of an irritant than a real danger, but it has to be done away with if direction-finding equipment is to be popular in the hands of unskilled personnel. On the last page of the paper the author states that the narrower the arc of silence, the less the possibility of errors being introduced from this cause. The logical deduction from this is that if for any bearing the required arc of silence can be brought down to the order of one or two degrees, the difficulties arising from fringe interference will disappear altogether. In practice this is actually the case; in fact, anything which can be done, artificially or otherwise, to reduce the arc of swing is a move in the right direction.

The paper affords confirmation of the view that there are three possible methods of attack on the problem of getting rid of fringe interference: (1) the universal use of tuned aerials for any system; (2) increasing receiver gain by straightforward high-frequency amplification; and (3) the more universal adoption of zero clearing or semicircular correction. On page 368 the author mentions that the majority of British beacons have been so regulated as to give a field strength of 50 microvolts per metre at their nominal working range. I suggest that this figure, in the case of the average mercantile installation, represents an arc of silence of something like 10° , and that until this condition can be improved very materially direction-finding operation, in view of the various forms of interference, must necessarily remain a process of greater skill than is commercially desirable.

Dr. W. F. Rawlinson: Since broadcasting became

such an important matter an opinion seems to have grown up amongst certain people that broadcasting and wireless communication are synonymous, and there is a tendency to look upon the communications of ships at sea as merely a source of interference with the broadcast programmes. The public, I think, tends to forget that for ships at sea the wireless installation is the only possible means of communication. It should be pointed out that the interference is not all one-sided, and that the broadcasting stations cause very serious interference with the communications of the mercantile marine and the Services.

I am very interested in the curves given in the paper for the characteristics of the spark transmitters, but I am not quite clear how the curves in Figs. 6(a) and 6(b) are obtained. These curves bear a close resemblance to the theoretical resonance curves of a pair of coupled circuits, but I find it rather difficult to see how the author obtains them with the spark-gap in the circuit. Was the spark-gap short-circuited, and are these actually the curves of a pair of coupled circuits; or was the transmitter working, and are they some sort of representation of the energy of the transmitter? If the spark-gap was short-circuited, then presumably the reason why Fig. 7(a) gives only a single peak is that when the spark-gap carries current the damping is so high that the circuits are no longer over-coupled.

By what he says on page 367, the author seems to imply that it is much easier to make a transmitter which will give constancy of frequency than to make a receiver which will stay on a given frequency. This is rather difficult to understand, because the transmitter and the receiver are subject to the same external temperature variations, but the receiver has the advantage that in general its power is supplied by batteries and its anode and filament voltages are more constant than those of the transmitter. In addition, local heating due to oscillating currents is very small in a receiver. My own opinion is that it should be much easier to make a receiver stay constant as regards its frequency than to make a transmitter which will always start up and remain on the same frequency. Perhaps the author will give us the reasons for his remark on this point.

Mr. E. B. Moullin: I should like to know why there is so much discrepancy in the minimum necessary field strength accorded to different wave bands. In the 1 800-metre wave-band a field strength of 2 microvolts per metre is referred to on page 355; later on, for the 800-metre wave-band, a figure of 12 microvolts is given; and when we come to beacons, 50 microvolts seem necessary as a minimum.

It surprises me—though I am sure that if I had the slightest experience in the work I should have known automatically—that the noise level is so troublesome in ships, while a coast station is regarded as peaceful in comparison. I presume this noise level is due entirely to the small electrical machinery in the ship, but I should have thought that where the wireless office is a large iron box the background noise would have been more easily cut out than in shore stations. Moreover, there is the possibility of quelling the noise at its source. I should be glad of information as to the precise meaning of that background noise, and the chances of quelling it.

At the top of page 357 the author mentions 66 per cent as the probable efficiency of any aerial used for broadcasting; I should like him to tell me just how this figure is arrived at. At what stage is the input of power reckoned, and is the output the power actually radiated?

Finally, there is a point of particular interest to me on page 365, where the author gives, as one of the sources of error in frequency during a transmission, the fluctuation of filament supply voltage. I should be grateful if he could give some explicit information as to what inherent or automatic regulation of voltage, in respect both of filament and of anode voltage, is normally to be found in ships. I am talking not of a large liner with expensive and perfect plant, but of a small ship with a relatively small and cheap generator. What is the normal equipment to be found there, and what degree of voltage regulation is maintained?

Major B. Binyon: I am especially gratified by the author's work in preparing the paper, because I recollect that in my Chairman's Address* to this Section in 1925 I mentioned that in connection with the transition from spark to C.W. and I.C.W. there was a very great need for the investigation of problems of this character, to ensure that all the functions for which spark communication is now employed could be performed equally effectively on C.W. and I.C.W. The present paper helps to clarify the position.

I think it seems fairly evident, from the numerous conferences which have been held, that the broadcasting organizations will, as spark communication ceases to be employed, probably want to make further inroads into the wavelength bands reserved for the mercantile marine service. Should that be the case, I should like to stress that all questions of the power of discrimination of the operator to utilize note differences and to concentrate his mind upon one signal and reject another should be ignored when making estimates of probable interference, because, as has been mentioned in the discussion, the tendency is, or will in all probability be, towards the mechanization of reception. We have the auto-alarm to-day carrying out a very important function, and its receiver cannot have the mental discriminating powers possessed by a wireless operator. To save time and labour, attempts have been made to make automatic direction-finding appliances. In connection with all these matters I think it is necessary to ignore the power of the operator's mind to discriminate between signals, and to have the bands used so protected that automatic reception can be employed.

There is one other point to which I should like to refer, namely the question of basing the interference figure upon field strength. So far as telegraphic signals are concerned, in my Address† to this Section I gave a table which showed that in the case of I.C.W., synchronous spark, and quenched spark, all having equal audibility, the field strength of synchronous spark could be less than half that of the I.C.W. or of the quenched spark. That is at least an indication that the interference derived from the synchronous gap of the same field strength as a quenched gap might be twice as great. This is an added complication which it might

* *Journal I.E.E.*, 1926, vol. 64, p. 83.

† *Loc. cit.*

be difficult to take into consideration, but I should like to point out that audibility, rather than field strength, is the real measure for interference so far as aural reception is concerned.

Mr. F. P. Best: For many years one has looked for some quantitative analysis of this question of interference, as opposed to the large number of qualitative analyses to which one has access. During part of the analysis made by the author I had the good fortune to be associated with him in one or two of the smaller laboratory measurements, and I found his methods of attack original and most stimulating.

Referring to Fig. 5(a), it will be noticed that the valve used to produce the very low decrement was of the old D.E.R. type. Various types of valves were experimented with, including most modern types, but the original D.E.R. valve was found to be the only one with a sufficiently straight characteristic to enable the decrement of a circuit, already as low as 0.01 without retroaction, to be reduced to as low a value as 0.001 by retroaction and still to remain stable when the grid was excited with a potential as high as ± 4 volts.

In Fig. 7(a) there are one or two points which appear to be interesting. The curve showing the envelope of the I.C.W. transmitter indicates clearly the physical reality of side-bands, and the fact that the modulation peaks are detuned only 0.2 per cent, i.e. 2 parts in 1 000, and yet are quite visible, shows the considerable accuracy which has been used in taking the measurements which the author has given us. Another interesting point is that the appearance of the side-bands gives a reasonable check on the decrement of the circuit used in taking these measurements. Taking the modulation percentage at about 95 per cent, as mentioned in the paper, the height of the side-band peak should be about 0.475 of the height of the carrier peak, plus any voltage due to the carrier itself when the low-decrement circuit is detuned 0.2 per cent from the carrier frequency. The effect of the other side-band may be neglected. A calculation based on these figures gives a decrement within about 10 per cent of that actually measured, and provides a satisfactory check on the stability of the measuring apparatus.

Captain A. J. L. Murray: The author shows very clearly in Fig. 2 how Brasov would interfere with any other transmitter in the waveband of 130 to 160 kilocycles per sec., but in Table 1 he gives the frequency band of 110 to 160 kilocycles per sec. as "Mercantile marine (exclusively)." He has explained to me that that is a figure of speech, because of course the Navy have a right to come in between 150 and 160 kilocycles

per sec., and we find the same interference from Brasov and Kaunas.

I should like to support what Major Binyon has said with regard to discrimination, and to point out that although it is very hard for the telegraphist to read morse through jazz, it does not make any difference to the man who is listening to jazz whether there is morse in it or not!

Commander J. A. Slee (*in reply*): Dealing with the remarks of Mr. Reed, the curve given in Fig. 1 is an approximate average of those taken from three different instruments, all of which include at least two tuneable circuits in addition to the ship's aerial. Fig. 3 is an approximate average of the curves taken from four different types of ships' receivers of different manufacture, which have only one tuneable circuit. The shape of the curve depends almost entirely on the degree of reaction which the operator may choose to employ. Such receivers give good selectivity in the presence of interfering fields not more than two or three times greater than the field of the wanted signal. With regard to the point raised at the end of Mr. Reed's remarks, the figures quoted are the average values of a very large number of observations and reports. There is no noticeable systematic variation of α with the relative bearing.

In reply to Dr. Rawlinson, the practical point is that it is now, and has for a long time been, the practice to build ships' receivers to cover an enormous range of frequencies, and in consequence the difference between two adjacent markings of the scale represents a very great change in frequency. There are very few receivers now in service in which the change in frequency is less than 7 kilocycles per sec. per graduation in the neighbourhood of 500 kilocycles per sec. The slow drift of the normal self-oscillating receiver is very small after the first half-hour.

Replying to Mr. Moullin, in the 1 800-metre band we can expect good operators, good receivers (with at least 40 decibels amplification), and a fairly quiet background. We have, also, the advantage of beat reception. Under these conditions a good operator can often read a signal from the very low field quoted. Generally speaking, only the large passenger liners operate in this band. Practically all ships work in the 600-800-metre band, and allowance has to be made for less skilled men, less available amplification, and a worse background. The beacons are used only for direction-finding purposes, and if allowance is made for the numerous instruments of old design which are still in service this figure is not unreasonable.

STRAIGHT-LINE DETECTION WITH DIODES.*

By F. ROBERTS, M.Sc., Associate Member, and F. C. WILLIAMS, M.Sc., Student.

(Paper first received 26th September, 1933, and in final form 15th March, 1934.)

SUMMARY.

An exposition of the principles of straight-line diode detection is given with reference to the direct production of an undistorted audio-frequency output voltage from a modulated radio-frequency input voltage. The exposition is accompanied by experimental evidence, which establishes the validity of the theory.

It is shown that by proper choice of circuit constants, almost perfect detection can be obtained, even with 100 per cent modulation. Both the theory and the experiments take account of the circuit coupling the detector to the next valve. The effect of positive bias is examined and is shown to be beneficial.

INTRODUCTION.

The problem to be discussed is that of recovering, from a radio-frequency input voltage modulated at an audio frequency, an audio-frequency output voltage which faithfully represents the modulation, with a maximum efficiency.

A properly designed diode peak detector will perform this duty almost perfectly, and attention will be confined to such detectors.

THEORETICAL INVESTIGATION.

Derivation of Equations, Neglecting Distortion.

A peak detector is one in which the input voltage charges a condenser C through a valve. If the valve has zero resistance in the one direction and infinite resistance in the other, the condenser potential will rise to the value of the highest input-voltage peak, and will remain at that value unless the condenser is leaky. Actually valves are not perfect rectifiers, but experiment confirms that it is possible, for the purposes here contemplated, to choose valves with negligible imperfections. As it is desired that the condenser potential should keep in step with the peaks of the input voltage, the condenser must be shunted by a suitable leak resistance R . For the major part of each radio-frequency cycle the condenser then discharges, and, in order to operate satisfactorily, the condenser voltage must fall to a value below the next peak of the input, so that for a transitory interval in the neighbourhood of this peak the valve will again conduct, and the condenser voltage will be reset on the track of the input peaks. If the input is an unmodulated

radio-frequency voltage of constant amplitude, then the mean condenser voltage will be less than this amplitude, because of the intermittent discharging. If the product RC exceeds $(10/2\pi)$ radio-frequency periods, then the mean condenser voltage will exceed 75 per cent of the peak value, which result is obtained by calculating the mean potential of the condenser in terms of its initial value over an interval of one radio-frequency period. The condenser voltage, which is also the "output" voltage of the detector, will consist of a radio-frequency component with a saw-tooth wave-form of constant amplitude, and a constant component approximately equal to, but slightly less than, the peak value of the input. For a modulated input the output will similarly contain an unwanted saw-tooth radio-frequency component with varying amplitude, and a useful component which varies in sympathy with the peak envelope of the input, but whose magnitude is normally slightly less than the corresponding ordinate of that envelope. This comprises the simple "peak principle," but its application to actual detectors must be adapted to suit further complications.

In practice the valve is shunted by unavoidable self-capacitance. In the absence of such capacitance, virtually the whole of the input voltage would produce potential drop across the valve, the slight discrepancy arising from the fact that the valve conducts for a small fraction of each cycle. Ignoring this secondary effect, it is clear that a capacitance shunting the valve will reduce the fraction of input voltage applied to the valve. If C_d is the capacitance shunting the valve, then, since we have already seen that the radio-frequency impedance of C should be much less than that of R , the fraction P of the input voltage appearing across the valve will be $C/(C+C_d)$, and it is the peak value of this "valve input" to which the condenser voltage is reset by the transitory valve conduction.

By tapping a portion of R any desired fraction of the total available output voltage may be obtained. As a rule it is undesirable that the constant component of the utilized output should vary as the audio-frequency component is varied, and for that reason the tapped portion of the leak is often resistance-capacitance coupled to the next valve. Typical arrangements are shown in Figs. 1 and 2, in which the coupling pair are marked R_0 and C_0 , and in which a battery yielding a positive bias of E_b volts is indicated. The input e is introduced at A , usually by means of a parallel tuned circuit. The symbols v_d , v_c , and v_o , represent the sums of the audio-frequency and constant components of the potentials developed across the condensers, and V_1 , V_2 ,

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

are the utilized output voltages. R_0 and C_0 tap a fraction a of the leak R . The audio-frequency reactance of C_0 is assumed to be negligible compared with R_0 , and $R_0 \geq R$. Subject to these and the previous restrictions, the valve input, i.e. that portion of the total input which appears as a potential drop across the valve, will still be a fraction P [$= C/(C + C_d)$] of the total input.

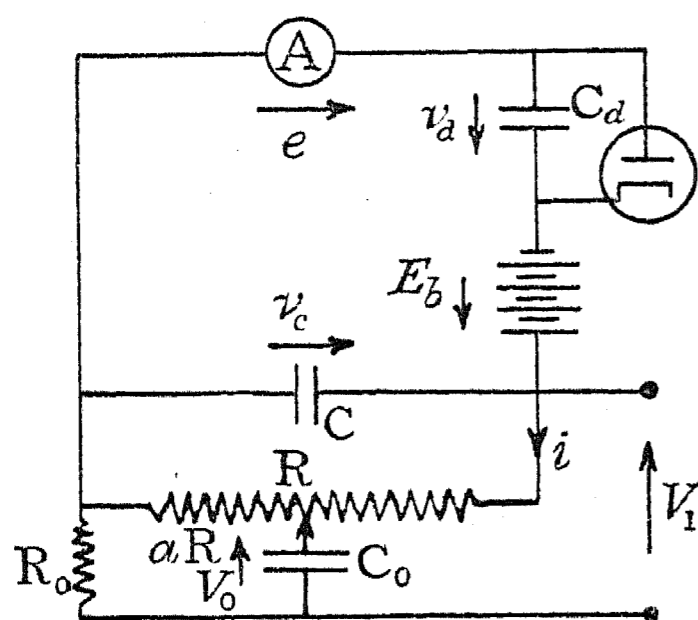


FIG. 1.

For "peak principle" detection to ensue, the negative bias which develops across C_d must be reset by transitory valve conduction in the neighbourhood of every positive peak of valve input, to the value of that peak, and, for this to be possible, R must be so small that the potential across C_d always falls between one peak and the next, to a value below that next peak. Failure to do this obviously cannot begin at a time when the peaks are rising, but, once having begun whilst the peaks are falling, may be continued for some time after the peaks have subsequently started to rise. If during any interval the resetting valve conduction occurs at every input peak, the detector is "tracking"; otherwise it is "non-tracking." Intermittent non-tracking is the principle source of distortion in the output from peak detectors, and this paper is principally concerned with the prevention of non-tracking.

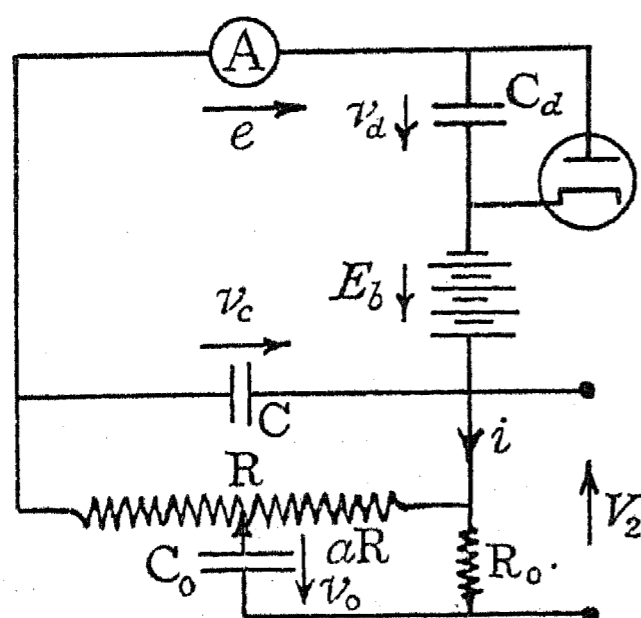


FIG. 2.

Even if non-tracking is absent, the output will certainly be distorted unless v_d maintains a negligible or constant difference from, or a constant ratio with, the peak envelope of the valve input. Assuming a carrier frequency at least 10 times greater than the highest modulation component, to a fairly close approximation the value of v_d at the instant halfway between any two successive input peaks will be the same as the average potential

across C_d during that interval. This average will depend primarily on the height of the initial peak and very little on that of the succeeding peak. It will also be less than the initial peak. The corresponding ordinate of the peak envelope at the halfway instant will be greater or less than the initial peak according as the succeeding peak is the greater or smaller of the pair. Consequently the ratio Q between v_d at any instant and the corresponding ordinate of the peak envelope of the valve input will depend not only upon the value of that ordinate, but also upon its time gradient, being less if the peaks are increasing than if they are decreasing. Tracking distortion is therefore inevitable, and it certainly appears that any reduction of R to prevent non-tracking will increase the tendency towards tracking distortion, but experiment shows that detectors which avoid non-tracking can be designed for which tracking distortion is negligible and for which the disparity between Q and unity is never great. We shall therefore ignore the tracking type of distortion, and shall assume as a first approximation that during tracking Q is uniformly equal to unity. For an input given by

$$e = E(1 + k \cos \omega t) \sin pt \quad (1)$$

we shall therefore presume that

$$v_d = PE(1 + k \cos \omega t) \quad (2)$$

and, corresponding to this variation of potential across C_d , we must have

$$v_c = E_b + PE(1 + k \cos \omega t) \quad (3)$$

$$v_0 = a(E_b + PE) \quad (4)$$

$$V_1 = (E_b + PE) + (1 - a)PEk \cos \omega t \quad (5)$$

$$V_2 = aPEk \cos \omega t \quad (6)$$

Condition for no Distortion.

If, with the above input, ϕ is the modulation phase angle at any particular input peak, valve conduction at this peak will reset the potentials of C_d and C to v'_d and v'_c respectively, given by

$$v'_d = PE(1 + k \cos \phi) \quad (7)$$

$$v'_c = E_b + PE(1 + k \cos \phi) \quad (8)$$

Thus, for the next discharging interval, the condenser voltages will have initial values given by (7), (8), and (4). Applying Thévenin's theorem to determine the current i (Figs. 1 and 2), it becomes evident that i flows in a circuit which in effect consists of a capacitance C_e [$= C + C_d$] in series with a resistance R_e [$= (1 - b)R$], where $b = a^2R/(aR + R_0)$, the time-constant T_e of this circuit being R_eC_e . The voltage E_e acting round this circuit will have an initial value E_e , given by

$$E_e = (1 - b)(E_b + PE) + PEk \cos \phi \quad (9)$$

If $C_d \ll C$ we are obviously justified in neglecting the radio-frequency input when estimating the value of E_e ,

both at the beginning and also for every other instant throughout the ensuing discharging interval. In any case, since the radio-frequency input virtually completes a full cycle during that interval, its overall effect on the value of E_e at the end of the interval should be of only secondary importance, and we shall neglect it. To a first approximation the final value of E_e will be less than E'_e by $(E'_e/T_e)(2\pi/p)$. On the other hand the value of E_e at the beginning of the next discharging interval following the presumed transitory valve conduction, will be less than E'_e (because of the change in ϕ) by $(2\pi/p)PEk\omega \sin \phi$. The condition for tracking to continue is, therefore, that

$$(E'_e/T_e) \geq PEk\omega \sin \phi \quad (10)$$

and the condition determining the inception of non-tracking and its attendant distortion of output is

$$E'_e/T_e = PEk\omega \sin \phi \quad (11)$$

Equation (9) may be written in the form

$$E'_e = E''_e(1 + k_e \cos \phi) \quad (12)$$

$$\text{where} \quad E''_e = (1 - b)(E_b + PE) \quad (13a)$$

$$\text{and} \quad k_e = PEk/E''_e \quad (13b)$$

If we compare the detector to which these equations refer, with a simple ideal detector from which the whole available output is taken directly, without the R_0C_0 coupling, and for which $C_d = 0$, and whose condenser and leak are equal to C_e and R_e , respectively, then all the analysis of the preceding paragraph will apply provided the assumed input e_e to the ideal detector is given by

$$e_e = E''_e(1 + k_e \cos \omega t) \sin pt \quad (14)$$

All the symbols with suffix e may therefore be termed the "equivalents" of corresponding quantities in the ideal case. In particular, T_e is the equivalent time-constant, e_e is the equivalent input, E''_e is the equivalent carrier amplitude, and k_e is the equivalent depth of modulation. Further, if $y = 1/k_e$ and $z = T_e\omega$, then y is the equivalent ratio of carrier to modulation, and z is the ratio of equivalent time-constant to the time required to execute 1 radian at modulation frequency.

In terms of y , z , and ϕ , the condition (11) for the inception of non-tracking becomes

$$y + \cos \phi = z \sin \phi \quad (11a)$$

The relevant solution, giving the value of ϕ at which non-tracking starts, is

$$\phi = \arccos \left[\frac{-y + z\sqrt{1 + z^2 - y^2}}{1 + z^2} \right] \quad (11b)$$

The condition for distortionless detection may now be

expressed by the condition that the solution (11b) be complex, which is

$$y^2 \geq 1 + z^2 \quad (15)$$

This condition agrees with qualitative expectations based on the preceding physical reasoning. From it, we see that detection will be distortionless for all depths of modulation "equivalently" below a critical value which depends on the modulation frequency and the equivalent time-constant of the system. For a given modulation frequency the critical depth is smaller the larger the equivalent time-constant, whilst for a given time-constant the critical depth is smaller the higher the modulation frequency.

We may also employ the same rule as a sufficient criterion for distortionless operation even when the modulation is of complex wave-form, if we use the value of y appropriate to the maximum depth of modulation, and the value of z appropriate to the highest frequency therein. For the corresponding forms of equations (1) and (10) respectively would then be

$$e = E[1 + \sum k_n \cos(\omega_n t + \theta_n)] \sin pt \quad (16)$$

$$\text{and} \quad 1 > \sum [k_{en}(z_n \sin \phi_n - \cos \phi_n)] \quad (17)$$

and, assuming that the different values of ϕ_n can assume all relative values, this is equivalent to

$$1 > \sum k_{en}(z_n^2 + 1)^{\frac{1}{2}} \quad (18)$$

Condition (18) will obviously be satisfied if

$$y^2 > z^2 + 1 \quad (19)$$

where $y = 1/(\sum k_{en})$ and z is the greatest value of z_n , i.e. that for the highest frequency in the modulation.

A typical detection requirement is that the process shall be distortionless for all modulations whose maximum depth is less than 80 per cent and whose composition may include any one frequency, or any group of frequencies, within the band 50 to 5 000 cycles per sec. For such specifications, since the modulation may as an extreme case be a pure note of 5 000 cycles per sec. impressed to the full permissible depth of modulation, it is evident that condition (19) is not only a sufficient but also a necessary criterion.

Returning to the consideration of a pure-tone modulation, we define the "bias factor" (α) and the "coupling factor" (β) by the equations $\alpha = PE/(E_b + PE)$ and $\beta = R/R_e = 1/(1 - b)$. It may be seen from equations (13a) and (13b) that the equivalent depth of modulation is the actual depth of modulation in the input, multiplied by the product of the bias and coupling factors, whilst the equivalent time-constant is obtained by dividing the actual time-constant T of the $(C + C_d)R$ combination by β . The condition (15) may also be written

$$1/(\alpha^2 k^2) \geq \beta^2 + T^2 \omega^2 \quad (20)$$

The value of β depends on the setting of the volume control; as α rises from zero to unity, β rises from unity

to $\beta_{max.} = 1 + (R/R_0)$. To avoid distortion for all settings it will suffice to consider the least favourable, which is that for $\alpha = 1$ with $\beta = \beta_{max.}$. With regard to α , if $E_b = 0$, $\alpha = 1$. If E_b is negative, $\alpha > 1$; and if E_b is positive, $\alpha < 1$. Obviously there is no point in using a negative bias, whereas by using a positive bias uninterrupted tracking can be assured in all cases. This fact is fortunate, for it permits the advantageous use of existing apparatus, but when new apparatus is being chosen it may be reckoned better to dispense with bias, if possible, by adjusting T to meet requirements. The condition then to be satisfied is

$$1/k_{max.}^2 \geq \beta_{max.}^2 + T^2 \omega_{max.}^2 \quad (21)$$

Principles of Design.

As a rule the output of a diode detector, working with an appropriate input of 10 or more volts, will be ample to operate the power output stage directly. Makers usually specify that the grid-filament coupling resistance for power valves shall not exceed $0.5 \text{ M}\Omega$. For that reason it will not be feasible to make $R_0 \gg R$, and a fair supposition is that $R = R_0$. The appropriate value of $\beta_{max.}$ is then 2.

There is, of course, no absolute necessity to use R_0 and C_0 . The output might be conveyed directly to the power valve. This would involve the simultaneous transfer of a steady bias voltage, which would always be sufficient to prevent distortion due to grid current, but which would perhaps lead to overheating of the power-valve plate for small inputs. If such be not the case, then the appropriate value for β is 1. Thus in all cases $\beta_{max.} \geq 1$, but in no case need β exceed 2.

On the assumption that the radio-frequency impedance of C must not exceed $0.1R$ if the preceding theory is to be valid, and if we assume the carrier frequency to be ρ times the highest modulation frequency, it follows that $T\omega_{max.} \geq 10/\rho$. Since, to satisfy equation (21), $T\omega$ must be small, and since ρ may upon occasion be as low as 10, we may adopt the rule $T\omega_{max.} = 1$ as a principle of design. Taking $\omega_{max.}$ to correspond to 5 000 cycles per sec., this yields that T should be approximately 30 microseconds, but if the radio frequency exceeds 50 kilocycles per sec. a smaller value of T will be permissible.

A useful interpretation of the rule $T \approx 30$ microsecs. is that if R be measured in megohms, and C_e in microfarads, then RC_e must be equal to 30; e.g. $R = 0.2$, $C_e = 150$; $R = 0.3$, $C_e = 100$; $R = 0.5$, $C_e = 60$. A value of C_e below $60 \mu\text{F}$ would probably mean loss in efficiency through reduction in P , whilst a value of R below $0.2 \text{ M}\Omega$ would probably mean loss of efficiency through excessive damping of the resonant input circuit by the detector load.*

If $T\omega = \alpha = \beta = 1$, as in the very simple case when the bias battery and indirect coupling R_0C_0 are dispensed with, and T has been suitably adjusted, then the tracking criterion (20) shows that up to 71 per cent depth of modulation can be accommodated without distortion. Moreover, calculation confirmed by experiment shows that distortion will not be important even at 100 per cent modulation.

If $T\omega = \alpha = 1$, and $\beta = 2$, then distortion begins at 45 per cent depth of modulation, so that, to avoid the very appreciable distortion which would exist at 80 per cent, α must be adjusted suitably by means of the bias E_b . Actually if we make $\alpha = 0.45$, 100 per cent modulation will be faithfully "detected." Since $P < 1$, a positive bias greater than or equal to 1.2 times the input carrier amplitude will be quite satisfactory. Another important principle of design is embodied in Figs. 1 and 2, namely that of minimizing the amount of radio-frequency input conveyed with the output, in contrast with circuits such as Fig. 7.

Analysis of Distortion and Possible Experimental Checks.

It may be noted that the audio-frequency output is in simple ratio with the audio-frequency components of v_c and v_d , which components are themselves equal. During the intervals when the valve is not conducting, v_c does not fall exponentially towards zero, but towards $E_a = b(E_b + PE)$, with the proviso that it cannot fall below E_b owing to the sudden inception of valve conduction at this juncture. If $E_a \leq E_b$, then, since even with 100 per cent modulation tracking never requires v_d to fall below E_b , the discharge voltage is still falling with considerable rapidity when tracking is resumed. This is characteristically true in the simple case when the R_0C_0 coupling is not used and $\beta = 1$. When $E_a > E_b$ —as, for example, when $\beta = 2$ and $E_b < PE$ —it may well be that for a considerable portion of the modulation cycle the voltage which v_c is required to track lies below the asymptote E_a . In that event the exponential segment of the output oscillogram, which indicates the non-tracking distortion, virtually reaches its asymptote long before the tracking is resumed, and the wave-form becomes apparently flat-bottomed.*

When distortion exists, the transition from the sinusoid to the exponential is not sharply defined on an oscillogram, because at the merging point the two segments have the same slope, but the theoretical angle ϕ at which distortion starts, measured from the positive crest of the sinusoid, is easily computed from equation (11b). The point at which tracking is resumed is sharply defined on the oscillogram. It is difficult to compute theoretically, but sufficient accuracy is easily obtained graphically, since the equations of both sinusoidal and exponential segments are known. Denoting the angle between the positive crest of the sinusoid and the next resumption of tracking by θ , an obvious experimental check on the validity of the theory which has been presented would be the comparison of the theoretical θ_T with the actual θ_A obtained oscillographically for representative cases.

For the purpose of a harmonic analysis of the theoretical output wave form, it is simpler to measure angles from the inception of distortion. Writing $\psi = \theta - \phi$ to denote the duration of the distortion segment, and $x = 1/z$, the value of the current i (Figs. 1 and 2) relative to its value i_0 when the same carrier input is unmodulated may be expressed as

$$1 + (\delta i_0/i_0) = a_0 + \sum_{n=1}^{n=\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \quad (22)$$

* See Reference (5).

* See also Reference (4).

where

$$\pi a_0 = (1 + k_e \cos \phi) [(\epsilon^{-x\psi} - 1)/(-2x)] + \pi - \frac{1}{2}\psi + \frac{1}{2}k_e \sin \phi - \frac{1}{2}k_e \sin (\phi + \psi) \quad (22a)$$

$$\begin{aligned} \pi a_n = (1 + k_e \cos \phi) & \left[\frac{n \sin n\psi - x \cos n\psi}{x^2 + n^2} \epsilon^{-x\psi} + \frac{x}{x^2 + n^2} \right] - \frac{1}{n} \sin n\psi \\ & - \frac{1}{2}k_e \cos \phi \left[\frac{\sin (n+1)\psi}{n+1} + \frac{\sin (n-1)\psi}{n-1} \right] + \frac{1}{2}k_e \sin \phi \left[-\frac{2}{n^2-1} - \frac{\cos (n+1)\psi}{n+1} + \frac{\cos (n-1)\psi}{n-1} \right] \end{aligned} \quad (22b)$$

$$\begin{aligned} \pi b_n = (1 + k_e \cos \phi) & \left[-\frac{x \sin n\psi + n \cos n\psi}{x^2 + n^2} \epsilon^{-x\psi} + \frac{n}{x^2 + n^2} \right] - \frac{1}{n} (1 - \cos n\psi) \\ & - \frac{1}{2}k_e \cos \phi \left[\frac{2n}{n^2-1} - \frac{\cos (n+1)\psi}{n+1} - \frac{\cos (n-1)\psi}{n-1} \right] - \frac{1}{2}k_e \sin \phi \left[-\frac{\sin (n-1)\psi}{n-1} + \frac{\sin (n+1)\psi}{n+1} \right] \end{aligned} \quad (22c)$$

and ϵ is the base of natural logarithms. With an obvious slight modification the same expressions indicate the harmonic composition of the output voltage. This harmonic analysis is subject to a restriction when the coupling $R_0 C_0$ is being used. Owing to the steady

$\alpha = \beta = 1$, and are shown in Fig. 3. It will be observed that 50 per cent second harmonic is the upper limit of the non-tracking distortion (subject, of course, to $\alpha = \beta = 1$). The existence of this theoretical limit accounts for the pronounced knee which appears in the

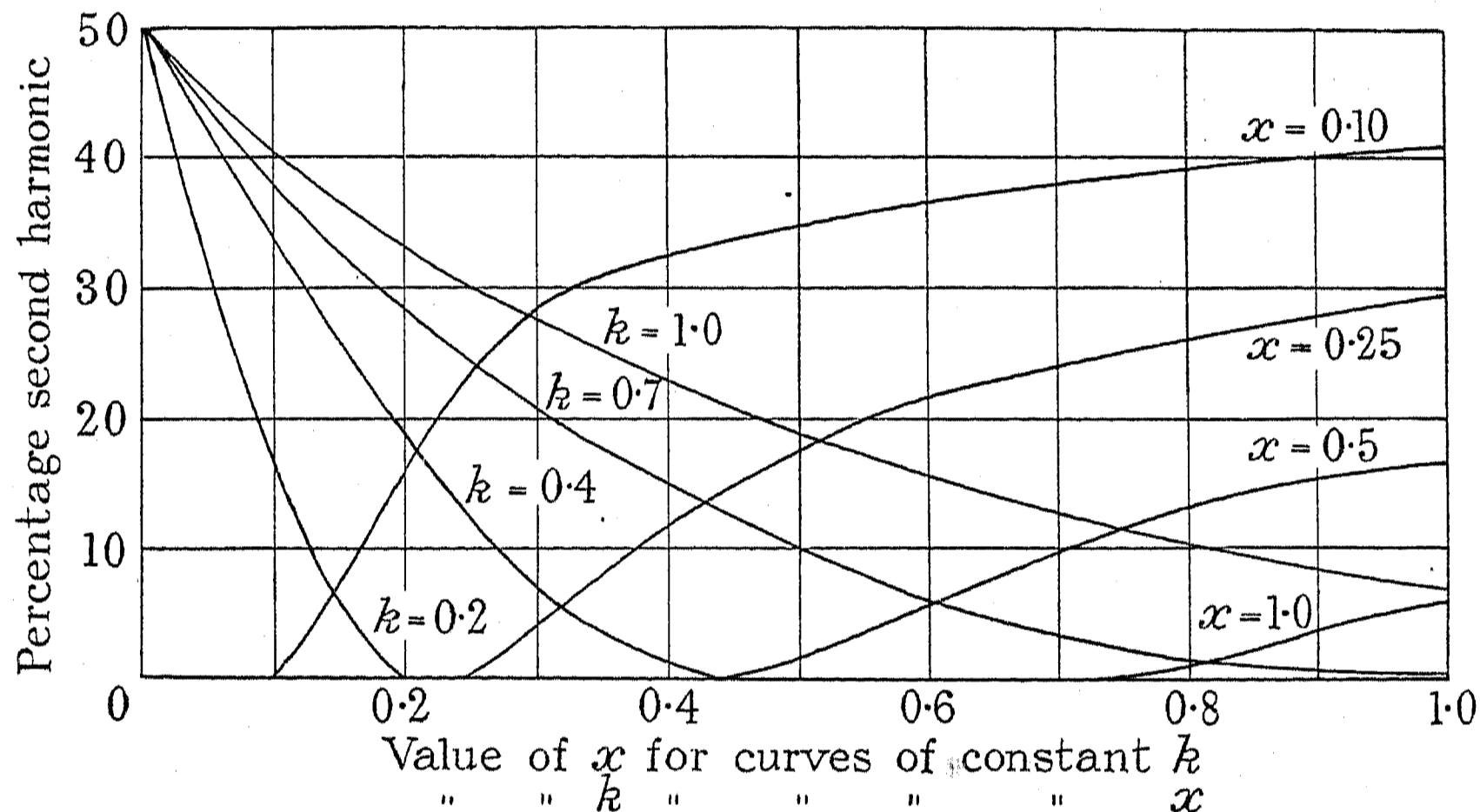


FIG. 3.

component of δi the mean potential difference across C_0 is correspondingly altered, but the effect is of a second order.

The analysis suggests two further experimental checks on the theory. Firstly, the constant component of δi may be calculated and also measured in representative cases. Such results are discussed below. Secondly, the output may be analysed by a harmonic analyser, and the results compared with the theoretical values, or, if the latter have not been calculated, such tests should reveal the critical depth of modulation or the critical time-constant, which may be compared with the theoretical values. This was the course followed by Terman and Morgan* and by Nelson,† working with $\alpha = \beta = 1$, since bias and output coupling were not taken into account. They found that the distortion consists mainly of second harmonic, and this finding agrees with theoretical expectation. Having no theoretical curves to check his experiments, Nelson supposed his results to be highly accurate, and to reveal a new kind of distortion. Theoretical curves have been worked out for the case

curve for $x = 0.1$. Nelson's curves corresponded to $x = 0.8, 0.4, 0.2$, and 0.1 , but whereas all should have shown the knee development, only that for $x = 0.1$ showed any signs of a knee, and the exception was so marked that Nelson suspected a new form of distortion. Moreover, all his curves crossed the authors' corresponding theoretical curves at a modulation slightly deeper than the critical value, the distortion being considerably less than the theoretical values for deeper modulations, and vice versa.

It must be admitted that the harmonic analyser deals directly with the distortion itself, but, since the degree of accuracy attainable by the method appears to be low, the authors preferred to photograph cathode-ray oscillograms of the output. A complete check on the theory is then possible by attempting to superpose the theoretical wave-form upon the actual wave-form. A slightly less rigorous check is imposed by a qualitative comparison of the actual and expected wave-forms, together with a quantitative comparison between θ_T and θ_A . It is unlikely that such a check would be in error, especially if supported by one or more checks of the more rigorous kind.

* See Reference (1).

† *Ibid.*, (2) and (3).

EXPERIMENTAL INVESTIGATION.

Simple Rectification Characteristic of the Diode.

Quite obviously it would be wrong to assume that during the reception of modulated inputs Q is always virtually equal to unity, if this same condition were not satisfied for unmodulated inputs. The performance of the valve chosen for such inputs under typical conditions

cident, for the same value of R . Curves were also plotted for $E_b = 2$ volts and $E_b = 20$ volts respectively, but the results were indistinguishable from those shown. It emerges that within the medium-wave band Q exceeds 90 per cent for inputs exceeding 10 volts (peak), and is approximately 95 per cent at 50 volts input. The 3 000-metre curves show Q to be 85 per cent for a 10-volt input. For larger inputs Q is of course greater, and

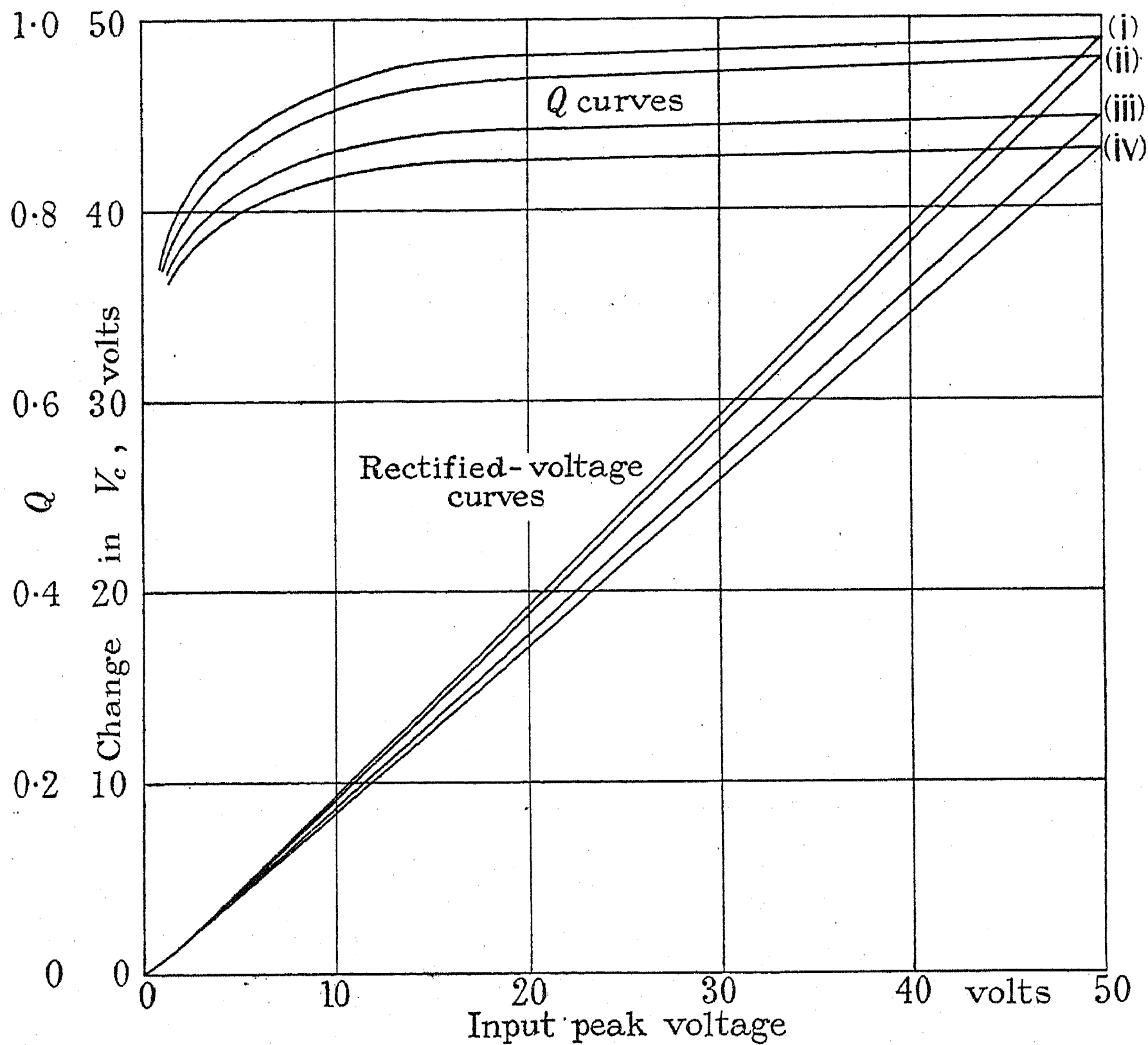


FIG. 4.—Curves obtained with an input frequency of 50 cycles per sec.

Curve	R	C	Equivalents	
			C	Frequency
	MΩ	μF	μμF	cycles per sec.
(i)	0.5	1.0	50	10 ⁶
(ii)	0.25	2.0	100	10 ⁶
(iii)	0.5	0.1	50	10 ⁵
(iv)	0.25	0.2	100	10 ⁵

is recorded in Fig. 4. The change in v_c , rather than v_c itself, was measured to correct for the effects of E_b and of contact potential difference between the valve electrodes. To facilitate rapid but accurate measurement, the tests were performed at 50 cycles per sec. For any given value of R , the results can be made to represent conditions at any radio frequency by suitable choice of C . If C_e is the capacitance which would be used at the radio frequency f , then $C = (f/50)C_e - C_d$ is the appropriate condenser value at 50 cycles per sec., but in point of fact the C_d correction is negligible. The curves corresponding to 300 and 600 metres are virtually coin-

since inputs ranging from 25 to 50 volts (peak) had to be used throughout the subsequent tests the assumption of $Q \approx 1$ was confidently made. Careful tests with small inputs showed that the simple rectification characteristics were linear down to 0.25 volt (peak) input.

Percentage D.C. Increment Versus Percentage Depth of Modulation.

Using equation (22a), the constant component of δi expressed as a fraction of i_0 was calculated for various values of k , taking as basic specifications, each in turn,

$x = 0.25, 0.5, \text{ and } 1.0$, with $\alpha = \beta = 1$ in all cases. The results are shown in Fig. 5, plotted against k . The value of k at which this fraction departs from the value zero, is of course the critical depth of modulation, and

measured at the input terminals of the rectifier by means of a slide-back voltmeter. In these tests R shunted the valve capacitance C_d , so that practically the whole of the radio-frequency input was developed across R together

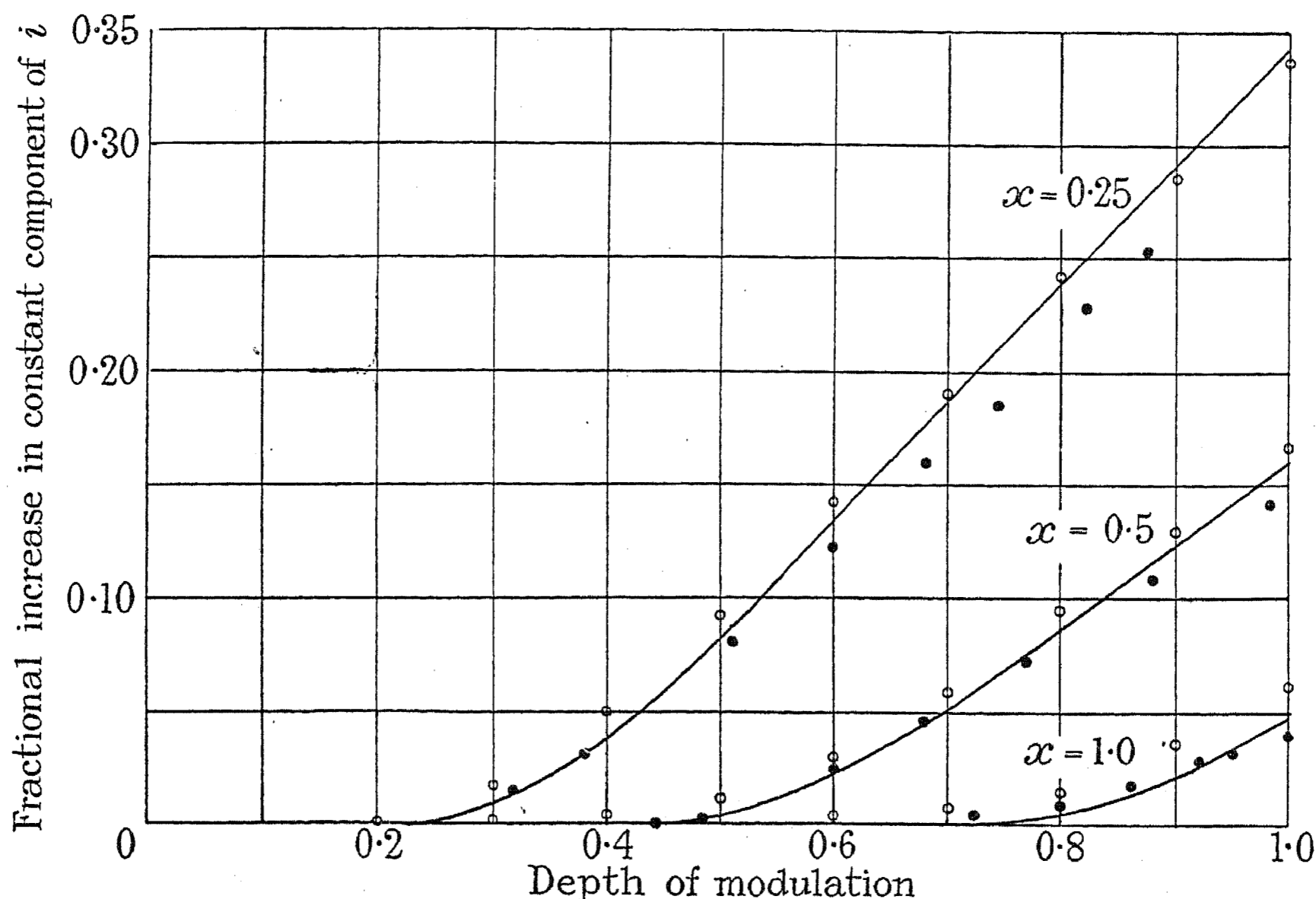


FIG. 5.

— Theoretical values.
 ● ● ● Observations with modulation frequency 200 cycles per sec.; $R = 4 \text{ M}\Omega$; input = 25 volts (peak).
 ○ ○ ○ Observations with modulation frequency 5 000 cycles per sec.; $R = 0.24 \text{ M}\Omega$; input = 50 volts (peak).

the value of this fraction for any deeper modulations is a measure of the distortion present in the output. Two sets of experiments were performed to verify these curves, with modulation frequencies of 200 and 5 000 cycles per sec. respectively, and these results are also shown in Fig. 5. The radio frequency was 710 kilocycles per sec. The apparatus used is indicated in Fig. 6. The radio-frequency oscillator was a simple shunt-fed type, and was choke-modulated directly by the output valve of the audio-frequency amplifier, a battery (B) being inserted to enable practically undistorted modulations to be impressed up to 100 per cent depth. The tests were made with the simple detector of Fig. 7, fed as there shown from a tuned circuit, which was shunted by a 10 000-ohm resistance to ensure a flat resonance curve, and also to render the input sensibly independent of the

with a steady bias due to rectifier action. In the arrangements of Figs. 1 and 2 the balance of radio-frequency input effect is to assist the discharge of C_d . In the circuit used for these tests the radio-frequency input similarly assists the discharge of C , which is normally much greater than C_d . Any divergence from theory on account of neglecting the discharging effect of the input should therefore be more evident than with the arrangements of Figs. 1 and 2. The agreement indicated in Fig. 5 justifies the neglect of this effect and also substantiates the theory of the simple case with $\alpha = \beta = 1$.

The Oscillograms.

Oscillograms of the detector output were taken photographically, with various conditions of circuit and input. The input-supply apparatus was similar to that for the

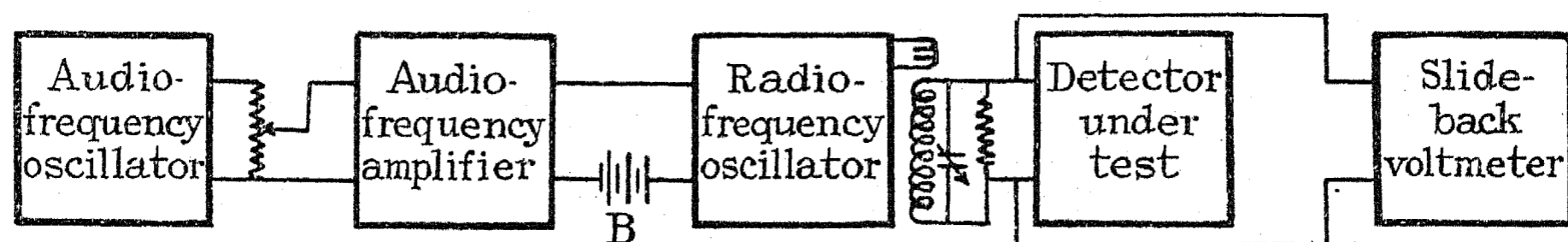


FIG. 6.

load imposed by the rectifier. The current through R , due to contact potential difference, with zero input, was negligible compared with that due to the inputs used. The correct value of C_d , allowing for all stray capacitances, was obtained by a simple substitution measurement after the detector apparatus had been assembled in position for the subsequent test. The depth of modulation was

previous test, the detector circuit being that of Fig. 8. The output voltage was led directly to the oscillograph. Oscillograms for eight typical cases are reproduced in Figs. 9–16, which indicate the type and value of evidence obtained from these and many similar tests, all of which confirm the theory.

The radio frequency used in the tests here recorded

was 580 kilocycles per sec., but other tests showed that this frequency might lie anywhere within the ordinary broadcast band without affecting the result. Figs. 9, 10, and 11, were obtained with a modulation frequency of 200 cycles per sec., and represent the full output of the simplest type of detector employing neither a bias battery nor a resistance-capacitance output coupling, the output being measured directly across R , so that $\alpha = \beta = 1$. The value of C_e was $198 \mu\mu\text{F}$, and R was $4.00 \text{ M}\Omega$, so that x was unity, and the critical depth of modulation was 71 per cent. The actual depth of modulation, and the theoretical and measured values of θ , are stated below the oscillograms, in all of which the motion is from right to left. The agreement between the predicted and actual values of θ is remarkably close, and the evidence of the "d.c. increment" tests is firmly upheld. Moreover, the distortion is so slight at $k = 0.8$ that the authors' recommendation, that in such simple detectors R and C should be chosen so as to make $x = 1$ at the highest modulation frequency, is justified. In one or two cases the authors have verified that if the entire curve, drawn as predicted from the theory, be superposed upon the actual curve, equally remarkable agreement is found throughout. The value of C_d was $20 \mu\mu\text{F}$, so that P was 0.90, and measurements with

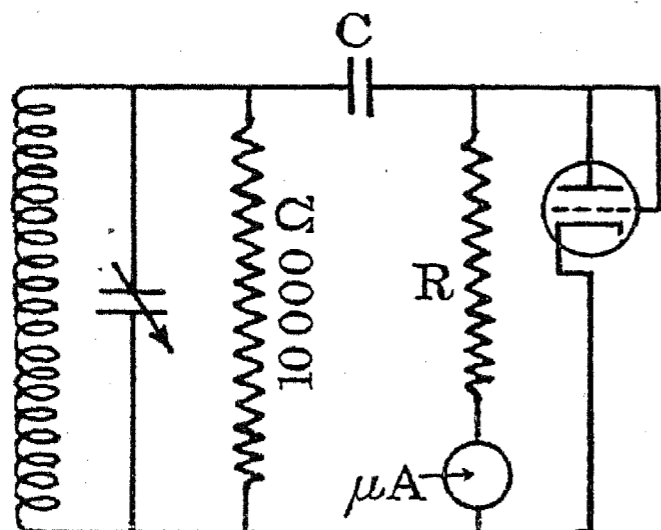


FIG. 7.

both the oscillograph and a thermionic voltmeter showed that the output amplitude was approximately 90 per cent of the input modulation amplitude.

The effect of taking the output through a resistance-capacitance coupling without using a bias battery is clearly shown in Fig. 12, for which $R_0 = 4.00 \text{ M}\Omega$ and $C_0 = 0.5 \mu\text{F}$, other conditions being the same as for Fig. 11. For Fig. 12, the equivalent depth of modulation was therefore 200 per cent as against an actual depth in the input of 100 per cent. This is obviously a case in which the asymptote of the exponential segment is virtually reached before tracking is resumed, and on that assumption, neglecting the slight increase in mean voltage of C_0 , θ_T would be 240° ; which is in good agreement with an actual value of θ of 250° , the discrepancy being of the sign and size expected on account of the relatively large d.c. increment through R , caused by the heavy distortion.

The theory of the detector complicated by the use of a bias battery as well as an output coupling is checked in Figs. 13, 14, and 15. The modulation frequency was 5 000 cycles per sec. The bias voltage was equal to the input carrier amplitude, which was the same for all eight oscillograms, i.e. 37.4 volts, a value chosen to yield suitably-sized oscillograms and to agree with an avail-

able bias-battery tapping. The other constants were $C_d = 20 \mu\mu\text{F}$, $C_e = 233 \mu\mu\text{F}$, $R = R_0 = 0.400 \text{ M}\Omega$, $C_0 = 0.5 \mu\text{F}$, and $\alpha = 0.75$; giving $P = 0.91$, $\alpha = 0.48$, $\beta = 1.47$, $x = 0.5$, $k_{e \text{ crit.}} = 0.45$, and $k_{\text{crit.}} = 0.63$. Fig. 13 corresponds to $k_{\text{crit.}}$, as found with the oscillograph, which is 5 per cent less than the theoretical value. The theory is therefore not seriously at fault, but it is worthy of note that in these complex cases the authors have always found the theoretical $k_{\text{crit.}}$ to be slightly greater than the $k_{\text{crit.}}$ determined experimentally. Since θ_T increases very rapidly to 180° as k increases beyond $k_{\text{crit.}}$, it is not surprising that θ_A exceeds θ_T by 30° in Fig. 14, and the divergence from theory is by no means as serious as would superficially appear. Fig. 16 was obtained with the same circuit and input conditions as in Fig. 15, except that C_e was $5\,850 \mu\mu\text{F}$ and the modulation frequency was 200 cycles per sec. The two oscillograms ought therefore to be the same, except for the slight modifications due to P being 0.91 for the former and 1.00 for the latter. Both oscillograms are in very good agreement with the theory.

The eight photographs were taken with the camera clamped at a standard distance from the oscillograph,

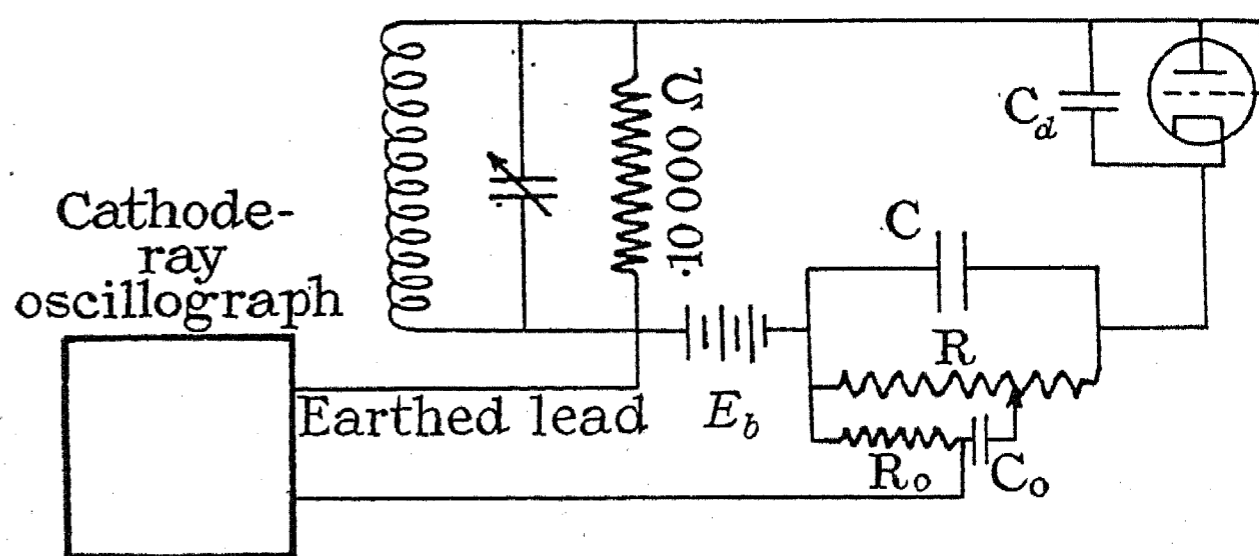


FIG. 8.

so that, except for variation in oscillograph sensitivity due to supply-voltage variation, the vertical deflections on all photographs are to the same scale. Thus the amplitudes of Figs. 9 and 13 should be theoretically in the ratio 1.69 : 1, and are actually in the ratio 1.65 : 1, whilst on account of the difference in P the amplitudes of Figs. 15 and 16 should be in the ratio 1.09 : 1, the actual ratio being 1.07 : 1.

It was found, presumably owing to slight dissymmetry of the electrodes, that the two deflecting directions were not exactly perpendicular, and that whereas directions of vertical deflection for different fixed horizontal settings were all parallel straight lines, for different vertical settings the directions of horizontal deflection converged slightly from right to left: hence the slight diminution in amplitudes in this direction observable on the photographs. The vertical line on each photograph is the direction of vertical deflection, and the angle θ was measured by projecting the peaks and kinks parallel to this line on to a single horizontal. The line was also central on the oscillograph screen, and is in a different position on the latter four photographs because the camera was moved laterally to bring the line nearer the centre of the photograph. The time-base was not perfectly linear, even over the centre of the screen. To

TYPICAL OSCILLOGRAMS OF DETECTOR OUTPUT.

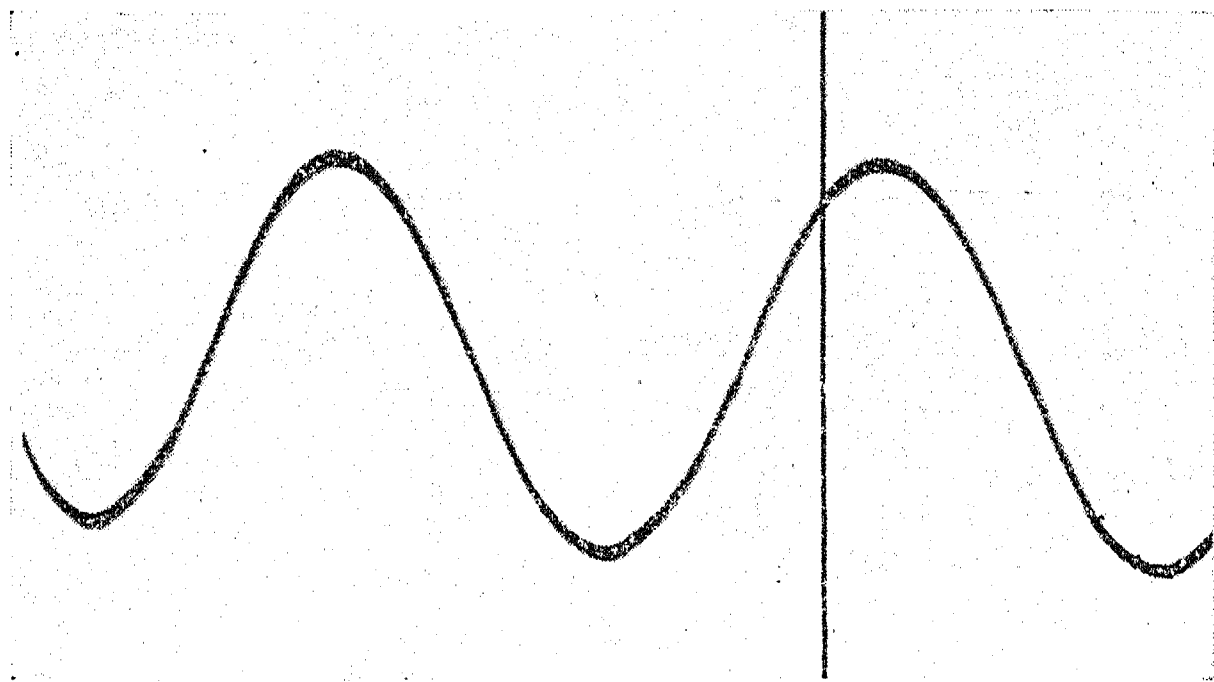


FIG. 9. $\alpha = \beta = 1; x = 1; k_{crit.} = 0.71;$
 $k = 0.75; \theta_T = 170^\circ; \theta_A = 172^\circ.$

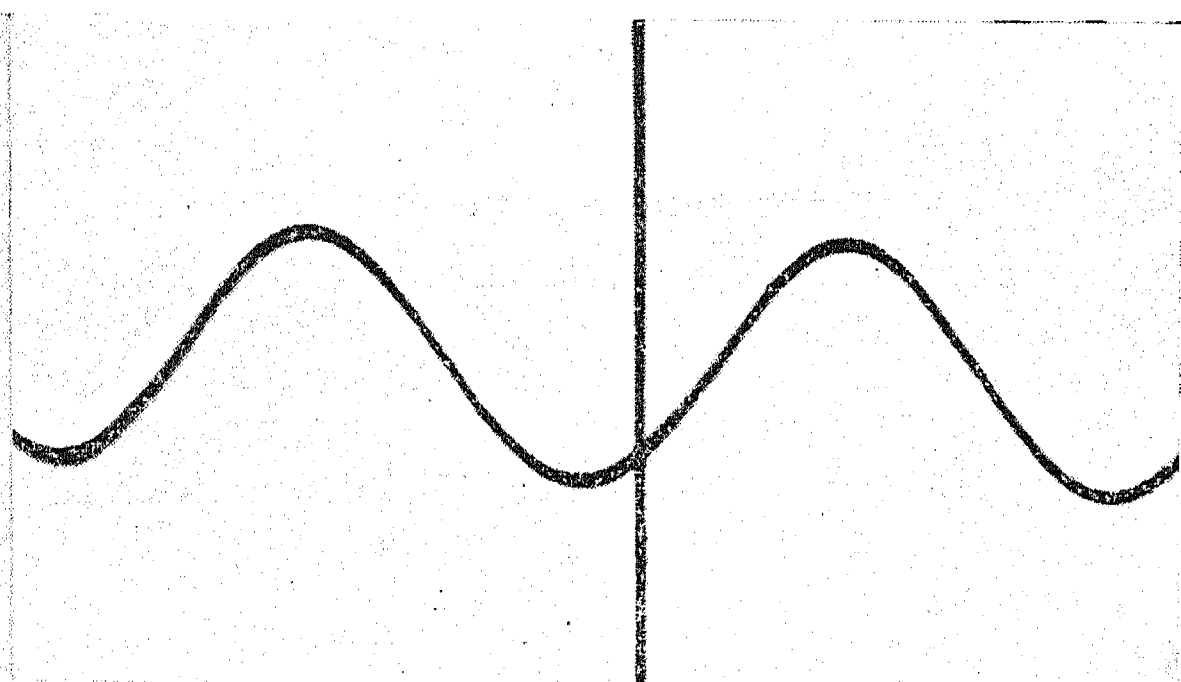


FIG. 13. $\alpha = 0.48; \beta = 1.47; x = 0.5; k_{crit.} = 0.63;$
 $k = 0.58 = \text{actual critical depth}.$

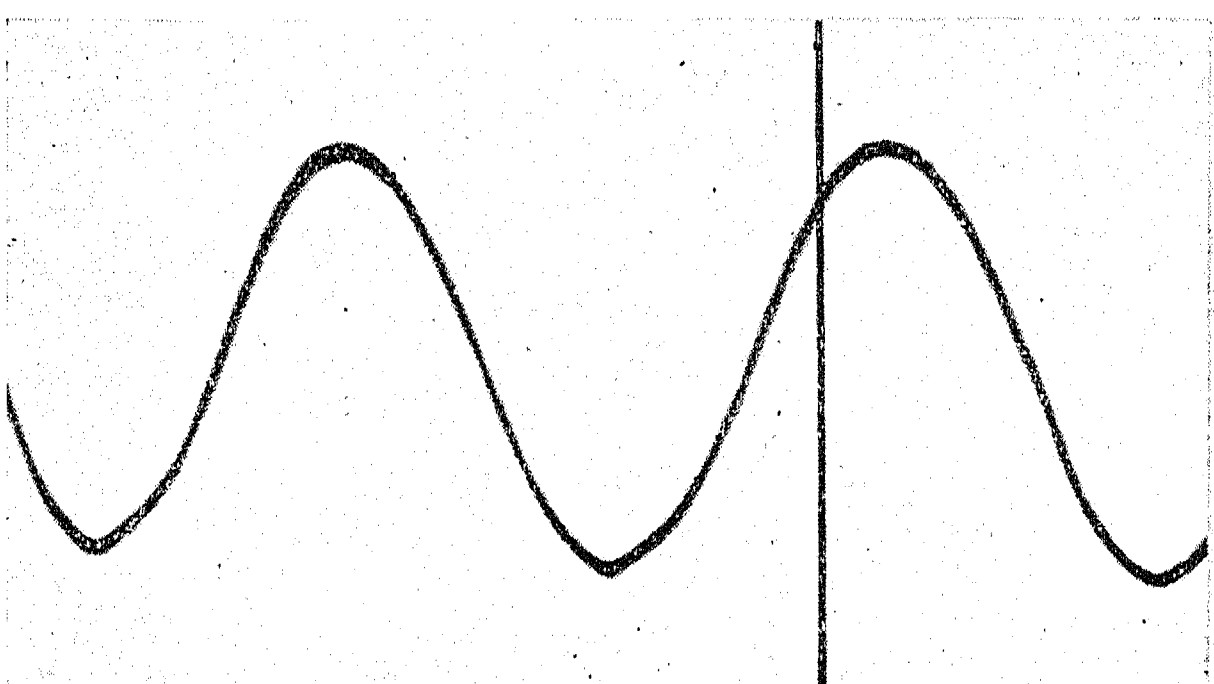


FIG. 10. $\alpha = \beta = 1; x = 1; k_{crit.} = 0.71;$
 $k = 0.80; \theta_T = 185^\circ; \theta_A = 183^\circ.$

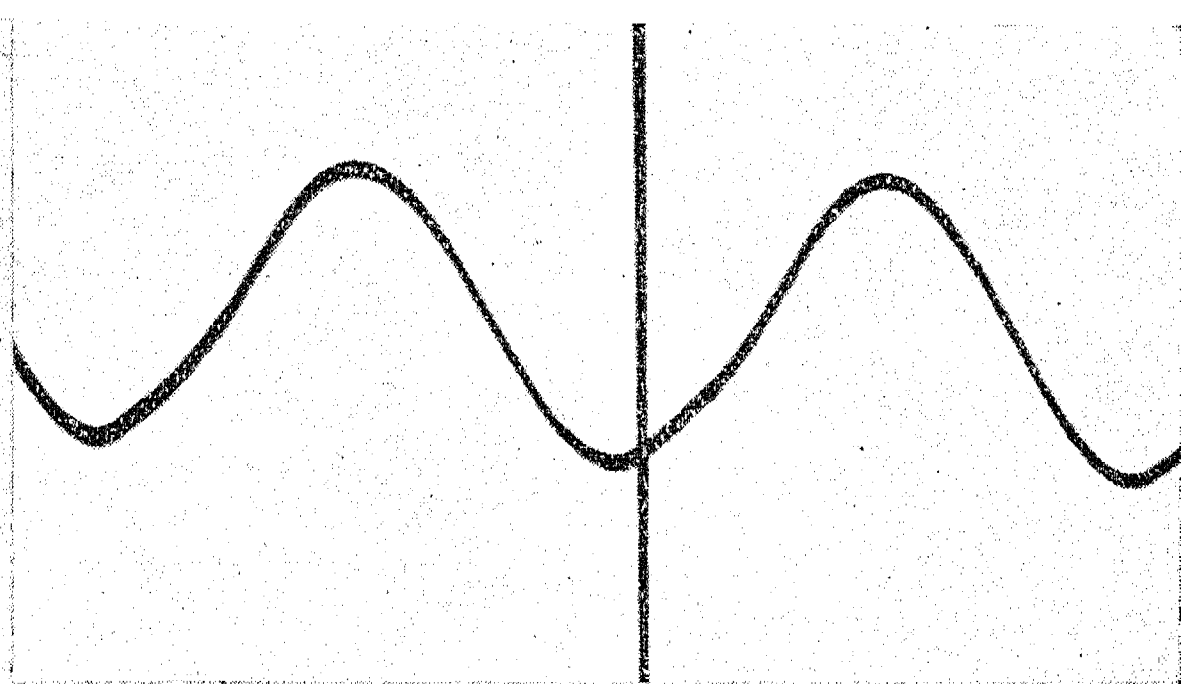


FIG. 14. $\alpha = 0.48; \beta = 1.47; x = 0.5; k_{crit.} = 0.63;$
 $k = 0.67; \theta_T = 150^\circ; \theta_A = 180^\circ.$

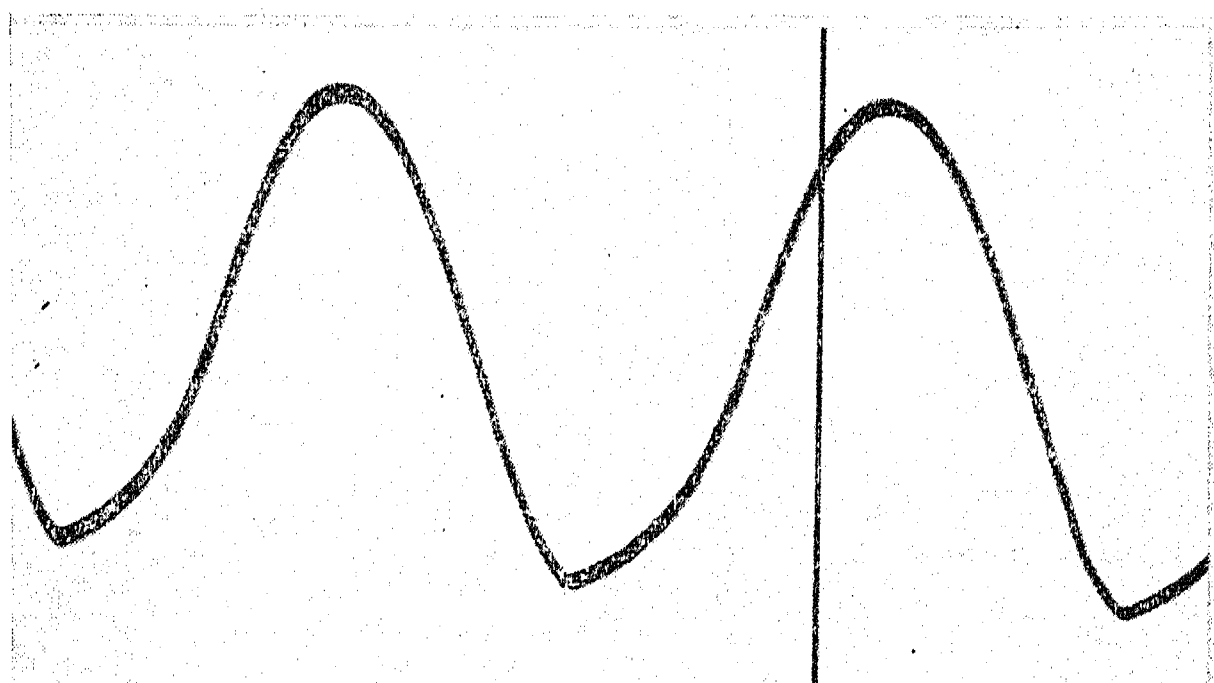


FIG. 11. $\alpha = \beta = 1; x = 1; k_{crit.} = 0.71;$
 $k = 1.0; \theta_T = 209^\circ; \theta_A = 208^\circ.$

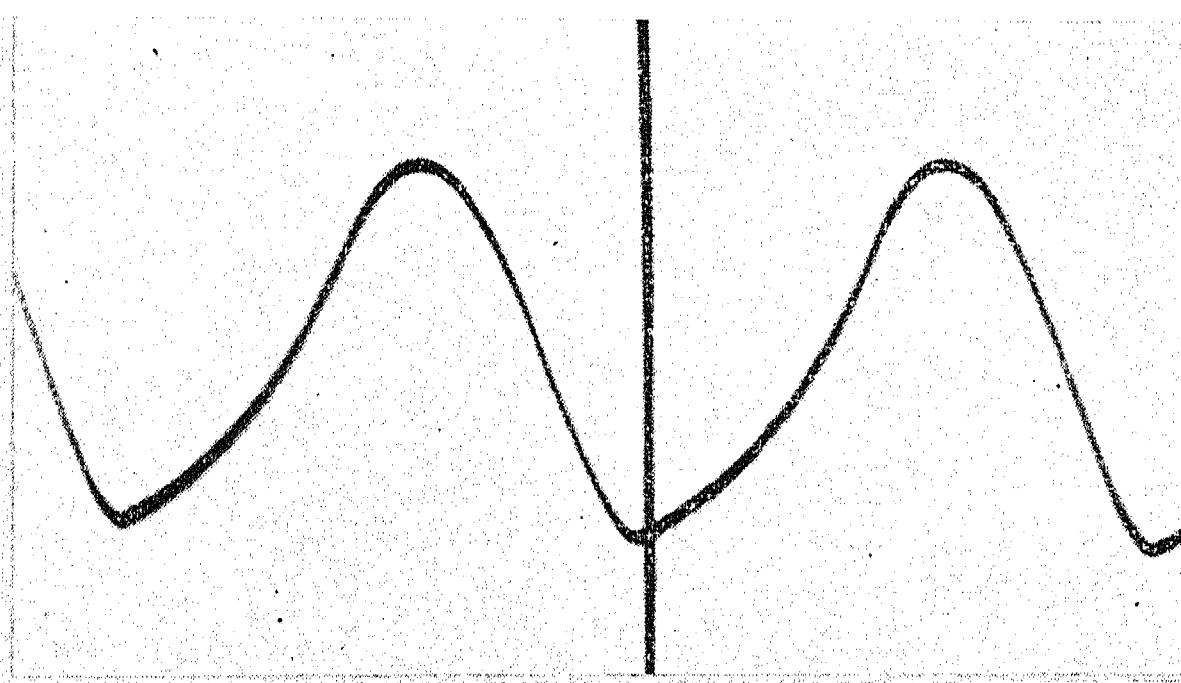


FIG. 15. $\alpha = 0.48; \beta = 1.47; x = 0.5; k_{crit.} = 0.63;$
 $k = 1.0; \theta_T = 207^\circ; \theta_A = 214^\circ.$

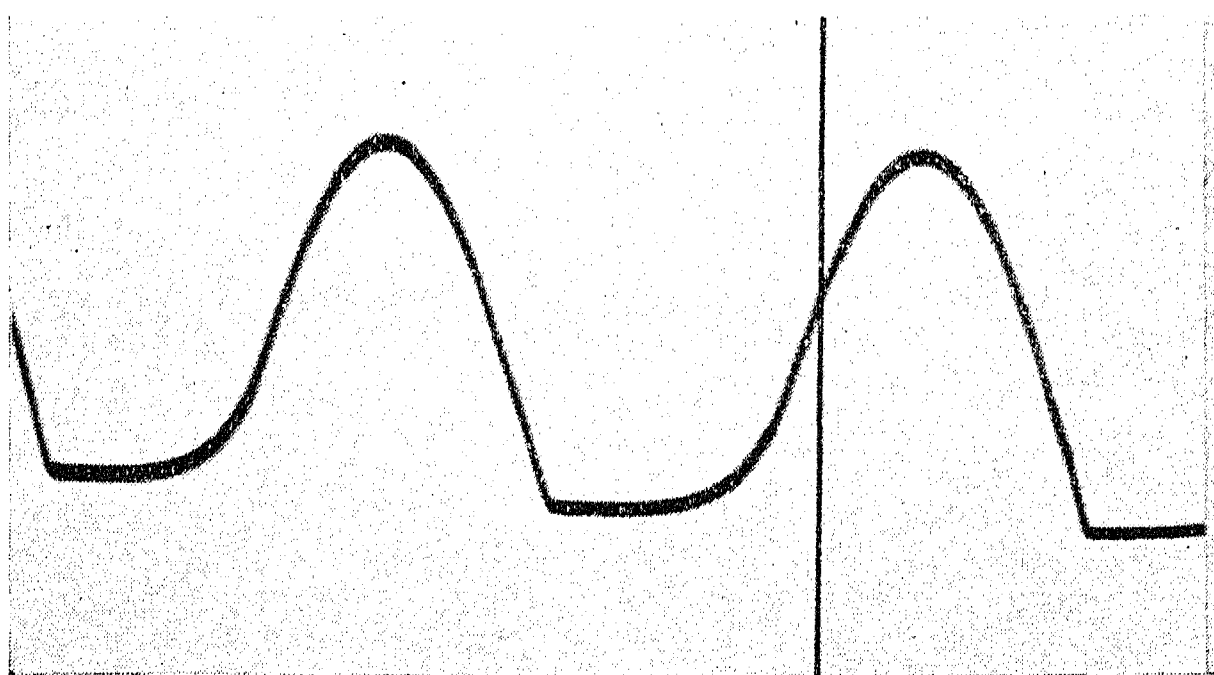


FIG. 12. $\alpha = 1; \beta = 2; x = 2; k_{crit.} = 0.45;$
 $k = 1.0; \theta_T = 240^\circ; \theta_A = 250^\circ.$

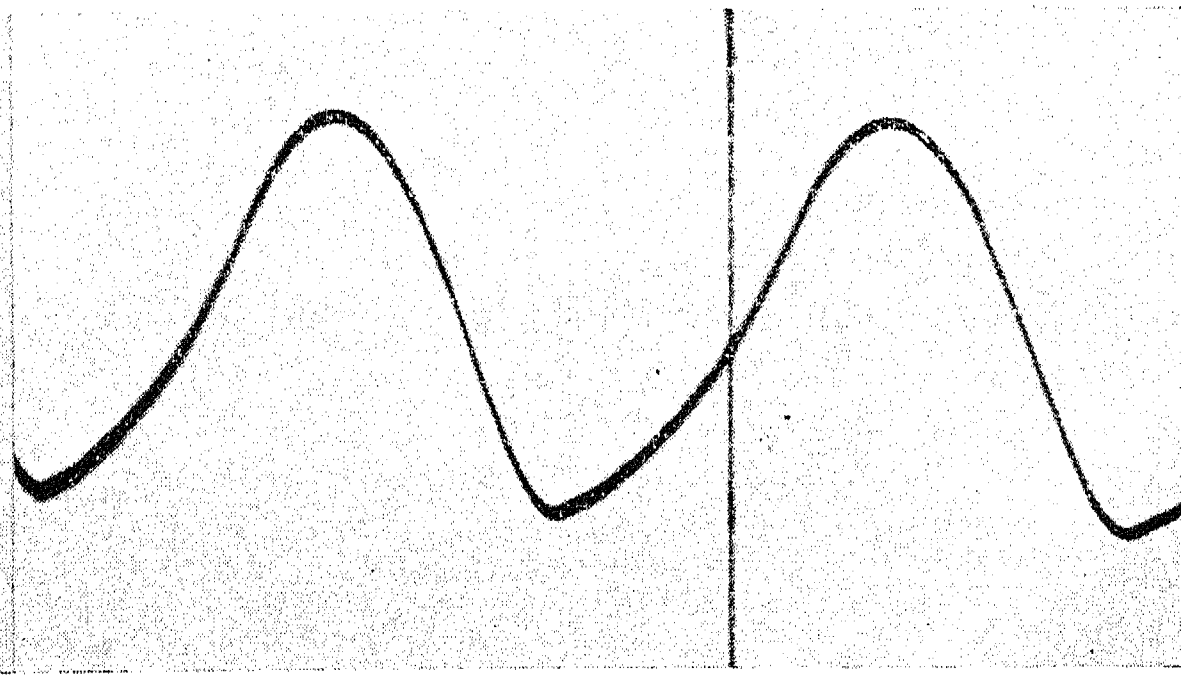


FIG. 16. $\alpha = 0.50; \beta = 1.47; x = 0.5; k_{crit.} = 0.61;$
 $k = 1.0; \theta_T = 209^\circ; \theta_A = 215^\circ.$

correct this, θ was obtained by comparing the interval from a peak to a kink with the mean of the intervals between the said peak and the succeeding peak, and the said kink and its predecessor.

CONCLUSION.

Although this paper has been concerned primarily with diode detection, the mode of reasoning can readily be applied to power-grid and power-anode detection problems, as well as to the dual problem of simultaneous detection and automatic gain control by means of a duodiode. It is hoped to deal with these problems later.

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NOTE ON A DEMONSTRATION OF A LOW-VOLTAGE ELECTRON MICROSCOPE USING ELECTROSTATIC FOCUSING.*

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INTRODUCTION.

The electron microscope derives its name from the ability of a beam of electrons to perform under certain conditions the same function as do the light rays in an optical microscope. Most of the work on the production of enlarged images of electron sources on fluorescent screens has been done with voltages of the order of several kilovolts, using magnetic focusing. A brief description of an electron microscope operating at 500–2 000 volts, focusing being obtained by electrostatic means, may therefore be of interest.

The electrode construction adopted is very similar to that described in the *Journal* by Zworykin.[†] Any form of high-vacuum cathode-ray oscillograph can generally be made to give an enlarged image of the cathode. As would be expected, however, the geometry for optimum definition and magnification in the microscope case differ somewhat from the geometry which conduces to optimum spot definition in the case where the electrode voltages are adjusted to give a spot on the screen.

When it is not desired to use the tube for oscillograph purposes, only one anode is required. In Fig. 1 this anode A is provided with an aperture a_1 which, like the aperture a_0 in the grid electrode G, may be regarded as the position of an electronic lens. The apertures

a_2 and a_3 , shown dotted, act only as stops, and were omitted in one of the tubes. Electrons from the cathode C suffer refraction on passing through the distorted electrostatic fields in the neighbourhood of the apertures, and under suitable conditions give rise to an enlarged image of C on the fluorescent screen S (see Fig. 4).

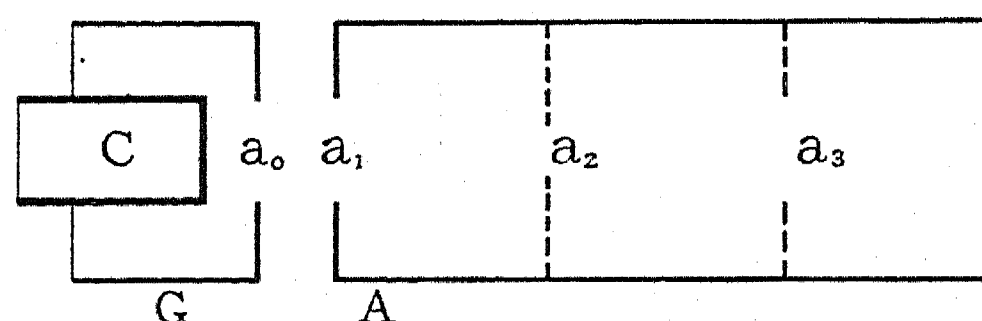


FIG. 1.

This image of the cathode is always inverted; an erect image would involve an additional electron lens.

THEORETICAL ASPECT.

Consider first of all the single-lens arrangement of Fig. 2. Here the anode has been omitted and the lines of electric force between C and G give rise to equipotential lines which present a concave surface to C, whether G is considered positive or negative with respect to C. Owing to the tendency of the electrons to follow the lines of force, we may clearly associate the equipotentials with a concave electron lens for electrons passing from left to right (G positive) or a

* The demonstration was given at the meeting of the Wireless Section held on the 7th March, 1934.

[†] See Bibliography, (1).

convex electron lens for electrons passing from right to left (G negative). We shall not have to consider the purely hypothetical case of electrons passing from right to left, for when we include the effect of A (Fig. 3) electrons will be able to pass from left to right even if G is negative, provided the potential of A is sufficiently positive to counteract the reverse field due to G . On inspection of the lines of force and equipotential surfaces we now find that the electron lens corresponding to G

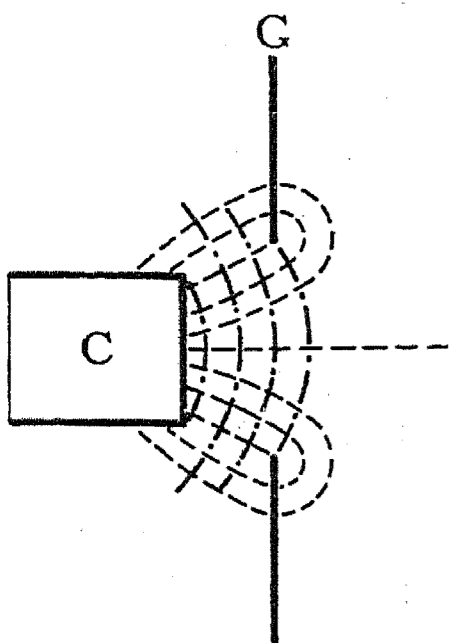


FIG. 2.

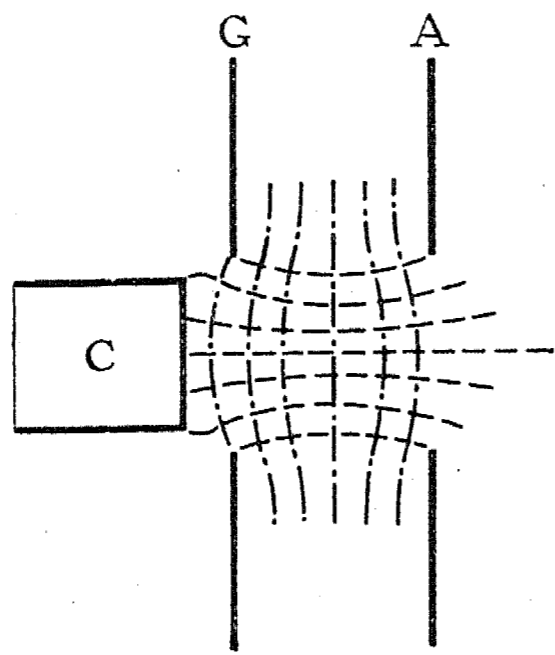


FIG. 3.

must change from concave to convex when the potential of A reaches a certain value depending on that of G .

C. J. Davisson and C. J. Calbick give a formula* which determines this change from concave to convex. It appears from their formula that the change in question comes about when a change in sign occurs in the quantity $(\epsilon_2 - \epsilon_1)$ which represents the difference, reckoned before the hole was formed, in the electrostatic fields in volts per cm existing on the two sides of G . The fact that when the change from concave to convex occurs the focal length passes through an infinity

experiment.* We shall therefore test this formula for the determination of the magnification to be expected in a typical case.

In the larger of the two tubes demonstrated, the voltages were +100 volts on the grid and +1000 volts on the anode. The distance Ca_0 (Fig. 1) was 0.238 cm, a_0a_1 being 0.50 cm. The values of f_1 and f_2 , corresponding to the apertures a_0 and a_1 respectively, are then: $f_1 = 0.145$ cm, $f_2 = -1.11$ cm. The lens action of the microscope appears to take place, then, quite locally, say over an axial length of about 1 cm.

The electron optical system constituted by two thin electron lenses of focal lengths f_1 and f_2 separated by a distance d ($= 0.5$ cm here) can be reduced to or replaced (as in ordinary optics) by a system of cardinal points, the chief of which are the principal foci (F_1, F_2) and the principal points. The latter are separated by a distance

$$h_1h_2 = -d^2/(f_1 + f_2 - d) = +0.171 \text{ cm}$$

The distances of the apertures from the principal planes are

$$a_0h_1 = f_1d/(f_1 + f_2 - d) = -0.0495 \text{ cm}$$

$$h_2a_1 = f_2d/(f_1 + f_2 - d) = +0.379 \text{ cm}$$

while the distance of the principal foci from the respective principal planes is given by

$$F_1h_1 = h_2F_2 = f_1f_2/(f_1 + f_2 - d) = +0.110 \text{ cm}$$

The magnification is given by the formula (see Fig. 4, not to scale)

$$M = F_2S/h_2F_2 = 30/0.11 = 273.*$$

The observed value of M was about 30 only.

In order to test whether an error in the focal lengths could cause this large discrepancy, a separate calculation has been made which shows that for the above positions

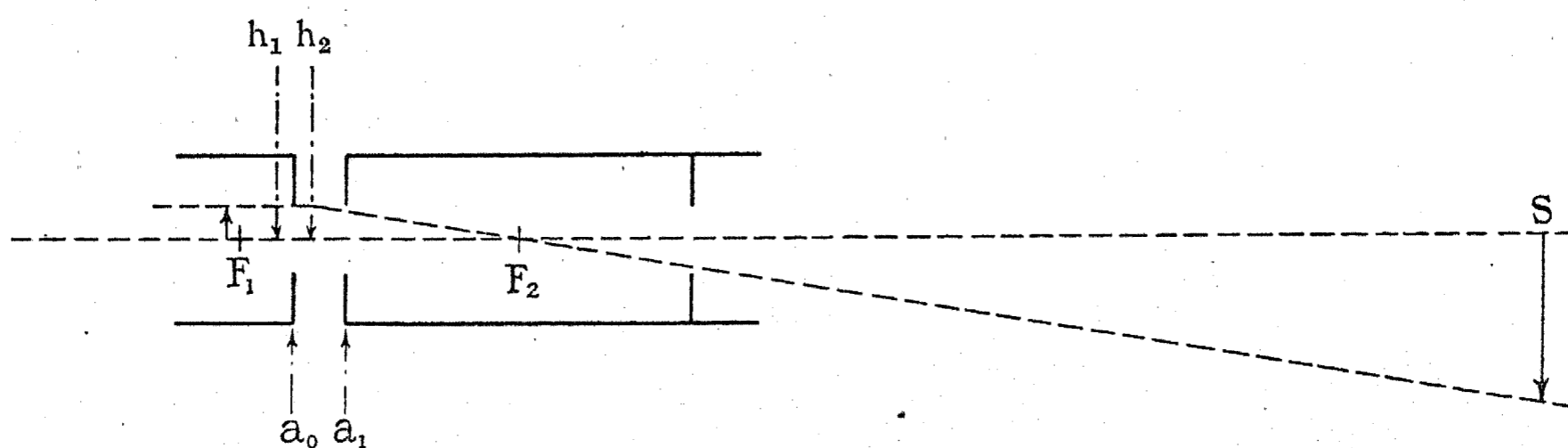


FIG. 4.

suggests that we should be able to express our focal length as some function of $(\epsilon_2 - \epsilon_1)^{-1}$. Since the higher the velocity of the electrons the less will they be deflected, we should expect the focal length (f) to increase with the electron velocity. The only other factor which might possibly enter into the expression is μ , the effective refractive index. We thus write $f = \kappa\mu v^p/(\epsilon_2 - \epsilon_1)^q$, where v is the velocity of the electrons expressed in volts and κ is a dimensionless constant. The only possible values of p and q , on dimensional considerations, are $p = 1$ and $q = 1$. Thus $f = \kappa\mu v/(\epsilon_2 - \epsilon_1)$. C. J. Davisson and C. J. Calbick gave, for an aperture of general shape,† the formula $f = 2v/(\epsilon_2 - \epsilon_1)$, which is stated to lead to results fairly well in accordance with

of the lenses, object, and image, the magnification cannot be less than 125 on the basis of ordinary optics, assuming the image is in proper focus. We conclude, therefore, that an error in the focal lengths cannot explain the discrepancy. We evidently cannot replace our electron lenses by thin lenses, coinciding with the apertures. The determination of the constants of the equivalent thick lens would involve a knowledge of the curvature of the equipotentials at all points.

According to the formulæ the magnification should increase with decreasing grid-anode separation d , thus shortening the focal lengths f_1 and f_2 . This prompted the design of a tube with increased magnifications, up

* See Bibliography, (2).

† Ibid.

* The author's attention has since been called to a later paper (*Physical Review*, 1932, vol. 42, p. 580) in which this is corrected to $f = 4v/(\epsilon_2 - \epsilon_1)$ for a circular aperture. This leads to a value of 133 for the magnification.

to 80 or so according to the electrode voltages. Thus while Davisson's formula does not appear to give good quantitative agreement with experiment,* it is possible to make use of it for design purposes. In general it is necessary to increase electron voltages in order to achieve an increase of magnification. The limit to the useful magnification is reached earlier than is generally supposed.

RESOLVING POWER.

It is widely held that the resolving power of an electron microscope is vastly superior to that of its optical counterpart. The resolving power of an ordinary microscope, measured by the reciprocal of the distance apart of two points on the specimen which it is possible to distinguish is given by $P_r = 2 \sin \alpha / \lambda_0$, where α is the angle subtended by the objective at the specimen and λ_0 is the wavelength of the light used for illumination. Taking $\alpha = 30^\circ$, $\lambda_0 = 5 \times 10^{-5}$ cm and $P_r = 2 \times 10^4$ cm⁻¹. In the case where electron waves are employed, the resolving power of the electron microscope appears at first sight to be of the order of $1/\lambda$, where λ is the wavelength of the electrons. As, however, λ has different values according to the emission velocities of the electrons, it is not possible to assign a value to λ which shall truly give the resolving power. For electrons emitted with a typical mean velocity of 2×10^7 cm per sec., the wavelength is given by

$$\lambda = \frac{6.55 \times 10^{-27}}{9 \times 10^{-28} \times 2 \times 10^7} = 3.64 \times 10^{-7} \text{ cm}$$

giving $\lambda^{-1} = 2.7 \times 10^6$ cm⁻¹

Owing to the spread in λ and to the resulting spread in focal length (by Davisson's formula) the resolving power of the electron microscope may be considerably less than this, while remaining perfectly satisfactory for practical purposes. A rough calculation in an unfavourable case gives $P_r = 2 \times 10^4$ for the resolving power for points near the circumference of the object. For axial points the resolving power may be considerably greater. For a resolving power of 2×10^4 the limit of useful magnification would be about 1 500.†

Another factor which can under certain circumstances destroy the resolution is the mutual repulsions of the electrons. By using a flat circular cathode with a central depression, different focusing conditions were observed as the temperature was progressively decreased. It was found that at high cathode temperatures the outer ring portion of the cathode was portrayed on the screen, whereas at lower cathode temperatures the depression in the cathode began to appear, the ring portion becoming fainter and finally disappearing as the depression came into focus. The conditions obtaining at the higher temperatures were such that the annular portion of the cathode was reproduced as a bright ring on the screen, but this ring showed up no details of the cathode owing to blurring effects arising from the high space-charge density of the cathode rays. The above result enables us to conclude that the focal length of the electron lenses

are shortened by increase of cathode temperature, i.e. the equipotentials become more curved.

The above may be regarded as confirming the effect of distributed charges on the divergence of the electric field as predicted by Poisson's equation.

APPLICATIONS.

The major application of the electron microscope is to the study of thermionically active materials. For example, in the development of such materials considerable time is saved if we can keep the materials under visual observation to ensure that the emission remains sensibly uniform under various conditions of temperature and space current. Materials which "fail" under the electron microscope will be immediately discarded, instead of, as at present, being subjected to prolonged life tests under conditions which do not permit of direct observation of their behaviour. By using an indirectly heated cathode marked off or suitably stamped into segments, a number of materials can be kept under observation at once, affording a comparative test and one which saves an immense amount of life testing.

The demonstration covered by this paper was made by permission of Marconi's Wireless Telegraph Co., Ltd., to whom the author expresses his acknowledgements.

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* The agreement claimed by Davisson requires the use of much smaller apertures than those used here.

† Since this was written a paper by Ruska has been published (*Zeitschrift für Physik*, 1934, vol. 87, p. 580) in which a method of obtaining a useful magnification of 10 000, by means of magnetic focusing, is described.

DISCUSSION ON

"THE BYPATH AUTOMATIC TELEPHONE SYSTEM."*

NORTH MIDLAND CENTRE, AT LEEDS, 9TH JANUARY, 1934.

Mr. C. A. Taylor: It has just been mentioned that I have returned recently from the United States, where they make extensive use of automatic equipment; but they have no bypath equipment.

The authors have made clear the many advantages to be derived from the bypath system. In respect of any system the ultimate test must always be a practical one, and the telephone authority in this country has therefore put the system to a practical trial. The authors naturally cannot produce evidence on the results of this trial, but we are all looking forward with interest to the results which will be available when the system has been in use for some time.

The ultimate test of any system is (a) its service efficiency, and (b) its cost, expressed as annual charges. With regard to (b), a high capital cost may be justified if the cost of maintenance is correspondingly reduced. It is somewhat difficult to assess the value of the bypath system without a knowledge of the capital and maintenance costs. With regard to (a), there are two points of importance. One is the reliability of operation and freedom from faults. The other is the transmission efficiency, which may be referred to as speech efficiency. The whole object of a telephone system is to enable one person to communicate his ideas clearly to some other person. There are many features subsidiary to that main principle, e.g. those of establishing connection quickly and of clearing the circuit at the end of the conversation. The fundamental and most important thing, however, is that one should be able to communicate clearly with a correspondent. It is possible to devise automatic equipment which will perform switching operations admirably but may degrade speech efficiency. The bypath system has the advantage that the bypath equipment is used only for establishing a connection and is thrown out of circuit after switching has been effected. It is possible, therefore, to employ for this purpose relays which will operate reliably as electromechanical switches whatever may be their effect on speech efficiency.

There is, however, a disadvantage in using equipment of this character, usually referred to as common equipment. I noticed while in the United States that American telephone engineers take elaborate precautions to detect a failure of common equipment. If one attempts to put through a call in a system employing common equipment, and the call fails, the fault is not always easy to find. There may be considerable difficulty in deciding which part of the equipment has caused the trouble. The director system in London already has common equipment, which is brought into operation during switching and then thrown out of circuit. If one

envisages the use of the bypath system generally in such an area as London, then, for many calls, there will be two trains of equipment which fall out at the end of the switching operations. The trouble involved in locating a fault is thereby increased.

With such a system calls may be lost, and it is important that the percentage lost should be negligible. The use of common equipment therefore requires to be very carefully considered, as it may have a serious effect on reliability of service.

Mr. W. D. Scutt: It has been obvious for many years that one development in automatic working would be in the direction of separating that part of the equipment which is absolutely essential for holding the conversation, and the main part of the equipment which is only used for setting up the call, and releasing that portion immediately after use. In that respect I think the authors have made out a perfectly good case for the bypath scheme. In a smaller way in the manual equipment at the Leeds trunk exchange we took what were complicated cord circuits and left them, actually, no more than a pair of straight wires. All the complicated parts of the circuit were thrown into a common pool with satisfactory results, just in the same way as in the bypath system. The system seems to be very good, and certainly lends itself to dealing readily with directional traffic over various exchange links. I am not quite satisfied, however, that the problems which the authors have solved for us can only be solved by the bypath system. The main advantage of the bypath system seems to me to be the saving in space and plant. Coming to alternative trunking, this, to me, is something new. I think that the idea of providing a direct group of junctions of relatively small size between exchanges and letting the overflow be dealt with by translation equipment, and be diverted through what we might term a common group, via a centre exchange, is an enormous advance and will clearly lead to very great economies in junction provision. As we all know, 20 junctions will carry far more than twice the load of 2 groups of 10, and so on. Whether the overall efficiency will be borne out in practice on the bypath system we shall know when experience of the equipment has been obtained.

I have four questions to put to the authors. First, reference is made in the paper to a facility on P.B.X. groups of being able to add lines to a group of exchange lines, independently of the numerical sequence. If that is quite as definite as I understand the authors to say, it is a wonderful advance. Where now we have to set apart a fair amount of valuable plant for P.B.X. services, we shall be able to associate these with ordinary direct lines. Is not a facility which may be regarded as equi-

* Paper by Messrs. J. H. E. BAKER and E. P. G. WRIGHT (see vol. 73, p. 1).

valent available at some Siemens exchanges? The authors will know that somewhere about the second group switch, a secondary switch carries the call on to a further uniselector, to the banks of which lines may be connected and P.B.X. groups formed without reference to numerical sequence. Secondly, in the case where the long-distance calls are carried through the centre exchanges on a common group, how is the differentiation made between local-area and long-distance calls? Local-area calls can use circuits of less efficiency than is required for long-distance calls. Thirdly, on alternative trunking, presumably, the alternative group would not automatically become available in substitution for the direct group should a breakdown occur on the direct group. Would some rearrangement by staff be necessary? Finally, assuming a P.B.X. group (say, 26 400-26 499) in which were no available spares, could any advantage be taken of spares in a further group of 100 in order to increase a P.B.X. group?

Mr. T. B. Johnson: Old telephone engineers will remember that, in the comparatively early days of the telephone, in exchanges with 600 or 700 subscribers it was necessary when a caller whose line was connected with one board wanted a subscriber who was connected to a board out of reach of the first operator, to employ junctions from section to section. The engineers of those days soon began to inquire whether all this junction switching could not be done away with. As we know, a multiple exchange was evolved which gave every operator access to every subscriber's line on the same exchange. It was at the cost of extra cable, but it saved the junction switching. It is not surprising that as soon as automatic exchanges were established people asked whether we could not do away with all this costly apparatus which was being locked up during the whole length of a conversation, an average of over $2\frac{1}{2}$ minutes, and often, of course, very much longer. It seemed for a long time as if the solution of this problem involved so much complexity and difficulty that there would be no gain in adopting it. The trials have gone on, however, and I think that practice will prove that the authors of this paper have found the solution. The extra cable does not cost much, and it does not produce many faults.

There are just one or two other points which have struck me greatly, in favour of this system. One, and I think almost the most important, is in connection with some tables which the authors have given in the *Journal** in response to inquiries and criticisms in London. They claim that an ordinary step-by-step automatic exchange where a length of 413 ft. of floor space would have been required in the early days, and 383 ft. now, can be got into 293 ft. by employing the bypath system. They further claim that whereas an exchange for 3 400 lines under the present arrangement involves a weight of $68\frac{1}{2}$ tons, the bypath apparatus would only weigh 43 tons. Now if those figures are confirmed in actual hard day-to-day practice they will represent an enormous advantage. If in a building, and particularly on the top floor, it is possible to substitute for a weight of 68 tons one of 43 tons, and to reduce the length from 383 to 293 ft., then the cost of erecting the building to house the apparatus will be very considerably diminished. It is the first

cost which has been giving concern to telephone engineers generally since the automatic system was first installed.

Another point is that, again on first principles, a continued rotary movement ought to be more simple and more satisfactory than a combined step-up and rotary movement. I think it is highly probable that this will be found to be true in practice as it is in principle.

A further advantage which has struck me very considerably is that subscribers who have sufficient lines need not have those lines adjacent to one another. In Leeds we have a lot of private branch exchanges. The *Yorkshire Post*, if I remember rightly, had something like 14 lines to the exchange. Those 14 lines had to be put on adjacent positions, and, although there was no difficulty about that, the trouble was that we had to estimate how many lines would ultimately be required. In this and many other private exchanges we had to leave a number of positions spare in order to make provision for an increased number of lines later on. I gather from the paper that this can now be avoided, and that subsequent lines can be added in any position about the exchange. That will save quite a considerable number of spare equipments which we had to leave vacant.

I am very glad indeed to learn that the Post Office is giving the bypath system a trial in two exchanges, one in London and the other in the provinces.

Mr. D. W. R. Fletcher: The bypath system appears to involve the substitution of rather more apparatus and the release of much of it as soon as the call is put through. The amount of economy available will therefore depend on the ratio of the time taken to put through the call to the total time occupied by the call. Have any investigations been carried out to determine whether this ratio can, in some cases, attain so high a value that the bypath system would fail to show any advantage?

Mr. G. S. Wallace: With regard to the banks of 100 or 200 lines shown on the screen, is it necessary that the traffic should be so arranged that these banks carry approximately equal loads? On the other hand, is an intermediate distributing frame necessary in the bypath system, as in an ordinary Strowger system? I do not see any mention in the paper of the voltage that is used on the bypath system. Is it 50 volts, or is any other voltage found more suitable?

As we all know, there are times when a lot of wires are out of order owing to storms, and faults occur over which no one has any particular control; does the bypath system cater for breakdowns such as might happen in the case of a heavy snowstorm? What happens in the case of a short-circuit? Are the line finders held up for any considerable time?

When a great number of faults occur, can steps be readily taken for isolating the faulty subscribers, so that they do not interfere with the ordinary traffic?

With regard to the rural automatic exchanges, what is the code size, and what will be the codes? It is obvious, of course, that no country subscriber would care to have to find five or six code figures in addition to the number of the subscriber whom he wants. Has any definite scheme been agreed upon in that respect, and, if so, is it in operation?

* See vol. 73, p. 26.

When one goes into a step-by-step exchange one hears a certain amount of noise. I should like to know how an ordinary bypath exchange compares in that respect with the other systems.

In an ordinary step-by-step exchange there are usually facilities provided for helping the subscriber who is in difficulties about dialling, especially when a new exchange is opened. Are any facilities of the kind provided on the bypath system?

Does the equipment provided at rural exchanges take more current than the ordinary Post Office standard rural automatic exchange? Not much provision is made for charging the batteries at rural automatic exchanges. If the equipment takes a lot of current it means fairly heavy batteries, and a gas plant or oil plant has to be arranged to meet this condition.

Mr. W. B. Crompton: With regard to the question of multiple metering, will the authors confirm that the subscriber's meter is operated by a booster battery? Dealing next with outlet selection, if R2 has to move over, say, 30 contacts before finding a free outlet to the next stage, is it possible for the subscriber to have sent the next digit before that outlet is found? In 2-motion switches only 10 contacts have to be searched.

Turning to the subject of maintenance, is common apparatus self-busy in the event of a fault developing which would cause a failure of a call? With the release of the bypath would there not be difficulty in tracing the route over which a call was set up? The authors mention on page 9 (vol. 73) that the system allows wider impulse limits; I should be glad to know whether this extension is appreciable.

As regards the automatic dial speed test referred to in the paper, I am not very clear as to what the method is and shall be pleased if the authors will tell us more about this. Under the present system the dials are tested by the test clerk.

I should like to ask a few questions in connection with the operating features of the bypath system. On page 10 there is a statement in connection with the completion of a trunk call in one stage. Is it meant that the call can be made via trunk offering circuit, or is it made over a junction? What is the risk of a double connection as compared with the standard system, i.e. two subscribers seizing the same bypath? What is involved in providing coin-box and party-line facilities, and is the arrangement complicated? Have the authors any information as to fault liability, particularly in connection with unattended exchanges? What happens if the common bypath equipment goes faulty? As regards alternative trunking, will the authors say how many transmission bridges are in the circuit when alternative routing is taken up? They deliberately provide insufficient direct trunks between two exchanges—A and B; the overflow, it is said, goes by C. In the latter condition, if there were an appreciable increase in transmission loss, would not this necessitate the provision of heavier conductors in the external circuit, and so in a measure reduce the saving which the authors endeavour to obtain under their scheme?

Mr. R. M. Longman: The system described by the authors has a distinct advantage in the procedure for calling a subscriber. Few people would care to have

to dial six figures before giving the subscriber's number.

The system described appears to have a considerable number of advantages for rural areas, for which an efficient telephone service is most desirable. In the country, if the telephone fails there is generally a big distance to traverse by road to communicate with the persons required, whereas in towns the alternative means of communication by trams and omnibuses are much more convenient.

The accommodation required in rural areas for exchange apparatus of the type described is very small; the street kiosk would probably meet the requirements, provided a supply of power for battery charging and for heating the kiosks were also available.

I should like to pay a tribute to the excellent work which has been done by the Post Office engineers in respect to rural telephonic development within the last five years.

Messrs. J. H. E. Baker and E. P. G. Wright (*in reply*): Although experience indicates that with director equipment there is a larger number of lost calls, is this in fact due to the greater use of common equipment? One is tempted to estimate that the lost-call percentage would be greater if the director system did not use common equipment. Cannot most of the increase be accounted for by the additional switching operations and the complications of key-sending and call-indicator working? If only one-half of a large provincial area were to be converted to automatic working and the remaining manual exchanges modified by the addition of key-sending and call-indicating equipment, no one would expect such good results as if the whole area had been converted to automatic working at once. These deductions are supported by the results of the bypath equipments operating in provincial and director areas. There is no evidence that the common equipment in the provincial exchange increases the fault liability. There is no reason to anticipate any difficulty in determining which set of bypaths has been used in setting up any particular connection, even if the bypaths have released, because in most cases only one bypath can set up any particular path. In the first and incoming stages, it may be either of two bypaths, but the associating arrangements are such that one or the other is indicated as the probable controlling element.

The bypath final selector has been designed with the object of taking full advantage of the possibilities of a uniselector for obtaining flexibility in the extension of P.B.X. groups. The arrangement of the circuit makes it possible for any number in an exchange to be the commencement of a P.B.X., and for any spare, dead, or changed number connected to the same final selector to be used as an auxiliary P.B.X. line. For night lines, spare numbers only can be used, because dead and changed numbers must be routed either to tone or an operator. The maximum capacity of the final selector is 200 lines, and no arrangements are provided for extending a P.B.X. group outside this group of lines.

Alternative trunking is available to handle unexpected overloading without any special action by the maintenance staff. In the case of a breakdown occurring on the direct route junctions, the associated relay sets

must be busied artificially. Calls via the alternative route use an additional transmission bridge. Normally, junctions to and from the tandem exchange use heavier conductors than the direct junctions, but this fact is not a serious disadvantage because the number of direct junctions which can be saved is so much greater than the number of additional indirect junctions which need be added.

Mr. Scutt has also asked how discrimination is effected between local areas and how long-distance calls are carried through the centre exchange in a common group. An example of this condition occurs in the Burton area, where the high-grade junctions to the satellites are available both to the Birmingham trunk operator and to other exchanges dialling in. Discrimination is effected by the first selector in Burton passing a signal forward to the satellite junction-line circuit to indicate that the special trunk signalling circuits should be used when the call originates from the Birmingham trunk board.

As Mr. Fletcher suggests, the economy of the bypath system depends partly on the ratio of the conversation time to the setting-up time. Investigations indicate that the economy would not disappear until the average conversational time was well below 1 minute.

Mr. Wallace asks whether the intermediate distributing frame (I.D.F.) is necessary in the bypath as in the ordinary Strowger system. Is an I.D.F. really necessary with the Strowger system? It is not a universal practice to use an I.D.F., and on the Continent it is the exception rather than the rule. The value of the I.D.F. is in part determined by the ratio of subscribers' line circuits to final selector numbers. When these quantities are equal, the provision of the facilities for handling inequalities in the various line-finder groups can be obtained more cheaply by additional finder banks and multiple cable than by the full I.D.F. Because the bypath system decreases the quantity of final selector numbers by the early re-utilization of dead and changed numbers, etc., it may be claimed that there is less necessity for an I.D.F. with the bypath system. On account of inter-exchange operation, 50 volts is the most convenient voltage. Line faults causing short-circuits are pulsed out of the first bypath after a short delay. These faults remain—holding the line-finder equipment and lighting a lamp—until the line is isolated at the main frame.

No scheme of common rural codes has been agreed upon for this country. On the Continent the codes usually contain 3 digits, but in some areas at the time of conversion to automatic operation only one or two digits are used, the other digits being introduced as the range of automatic connection extends. It is difficult to make any definite comparison between the Strowger and the bypath systems as regards noise and rural-exchange battery consumption. The noise is somewhat different in character on a bypath system, and there are no equivalents to battery-consumption figures. With the Strowger system, assistance is given by the operator

calling back the subscriber by means of the trunk offering train. The operator is then listening through condensers, so that the subscriber is free to dial again. With the bypath system, the condensers are introduced into the "O" level circuit by a special assistance key, and in consequence the operator is saved the time and trouble of re-establishing the connection.

In reply to Mr. Crompton's question on metering, the bypath system uses a booster battery to signal when metering should take place. The signal is carried from the first switching stage to the subscriber's meter over a fourth wire. The 20-group Strowger selector searches two outlets at a time at a speed of approximately 32 steps per sec. The bypath R2 tests two outlets at a time also, but steps at approximately double the speed. In normal circumstances an accessibility of 50 outlets may be arranged, taking approximately 400 millisecs. It should be pointed out that adjacent groups cannot be so large, as time must be allowed if R2 is not standing at the beginning of the groups. Where a 200-outlet selector is used there will be two R2 switches, and these can be arranged to handle alternate groups.

The bypath circuits are as far as possible self-busy. Failure of certain relays to release, or the associated unselector to return home, results in the circuit testing busy. The wider impulsing limits may be expressed by the fact that the unselector moving on the release rather than the operation of the armature requires 20 per cent less time to operate than the vertical magnet of the Strowger switch. The automatic dial-speed test is intended to be operated by linesmen without reference to the test clerk. The proposal was developed because it was considered that linesmen would make more checks with a machine than with the assistance of a test clerk. The plan has obvious advantages in rural areas. The linesman obtains access by dialling a special code and listens for a "number unobtainable" tone. By replacing the receiver, the bell may be tested by the ringing current which is returned from the dial-speed test circuit. On removing the receiver a second time, the speed may be tested by dialling "O," the conditions fast, slow, and normal, being indicated by different tones. The tester comprises a unselector stepping at 30 steps per sec., the tone being controlled by the movement of the unselector during the 10 impulses.

A trunk call is completed by a special incoming circuit with the assistance of the normal penultimate and final bypaths. Should the called number be engaged, the operator can offer the call by throwing the ringing key and subsequently completing the connection if it is accepted by key operation. The risk of double connection is obviated by the use of battery testing at all switching stages. Coin-box party-line facilities are provided in much the same manner as at present.

Sufficient evidence is available to indicate that the use of common equipment may be justified for unattended exchanges, but we have not sufficient results to permit comparisons being made as to fault liability generally.

DISCUSSION ON

"THE SPONTANEOUS BACKGROUND NOISE IN AMPLIFIERS DUE TO THERMAL AGITATION AND SHOT EFFECTS."*

Dr. F. B. Llewellyn (U.S.A.) (*communicated*): The paper contains a comprehensive theoretical and experimental study of the various sources of noise in vacuum tubes and their associated circuits. The point of view throughout is consistently independent, bearing little resemblance to those adopted by earlier writers in the field. It need hardly be said that such an independent study is stimulating and represents a welcome addition to the literature on the subject.

The American reader will be most gratified by those parts of the paper which lead to the same formulæ as had been derived in the United States. This applies in particular to the formulæ for shot-effect noise in the absence of space charge and for the noise caused by the thermal agitation of electricity in conductors. In both of these cases the results of the authors for the specific case treated by them agree with the more general results of T. C. Fry† and H. Nyquist‡. On the other hand, the portions which disagree with earlier studies, though they do not represent as pleasant reading, may actually prove to be more valuable in the end because of the opportunity they provide for reconsideration and clarification of the questions at issue.

Such an instance arises in the treatment of noise under actual operating conditions, where the results differ widely from those which I obtained several years ago.§ Since the authors specifically state that they do not understand my argument, I shall attempt in this communication to clarify some of the details they appear to have found obscure.

Before doing this, however, it may be well to point out that the ultimate test of any such theory must be furnished by experiment, since the final purpose of the study is to search out the true state of affairs as regards noise and not to build up a mathematical argument for its own sake. Unfortunately, in the case in question, the experimental findings are in general very discordant, different tubes and different circuits yielding widely diverse results. Hence it is not possible to say of either formula, "It must be right, because it agrees with all the facts." In spite of this, however, the experimental results do seem to offer conclusive evidence that the formula (17) obtained by the authors is wrong.

To see how this comes about it is only necessary to observe that the formula under discussion purports to give the amount of shot-effect noise under conditions of complete space-charge limitation. In an actual tube this may be *augmented* by the noise from a variety of

other causes, such as the thermal agitation of electrons and the flicker effect, and it also may be increased by incomplete temperature saturation. There appears, however, to be no way of *diminishing* it. In other words, the formula should represent an absolute minimum below which tube noise cannot go. Now when we compare the observed noise with that predicted by my formula, we do find in fact that in general the observed noise with complete space charge is always the greater; but it is less than that predicted by the authors.* This, as I see it, leaves the burden of defence decidedly upon their side.

Returning now to the aspects of my theory which the authors found obscure, I shall first attempt to clarify the problem by setting down the fundamental characteristics and properties of the flow of electrons; first without any space charge, and secondly with complete space charge. This I shall do in the form of the following brief, where I have attempted to arrange the items in accord with the steps in a logical reasoning process; beginning with the hypothesis on which the argument rests, next introducing experimental evidence, then deduction, and finally reaching a conclusion in each case:—

(1) *With no space charge.*

Electrons leave the filament independently of one another.

The random variations in the rate of emission determine the variations in current.

This is not affected by initial velocities, and hence depends on filament temperature only to the extent that the temperature determines the average rate of emission.

The internal tube resistance is infinite.

Variations in current are determined solely by variations in the rate of emission.

(2) *With complete space charge.*

The actual emission takes place in the same manner as above.

Space charge returns most of the emitted electrons to the filament.

Changes in the rate of emission do not affect the number of electrons reaching the plate.

* With their own tubes, illustrated in Figs. 22 and 23, which seem never to have saturated well, the excess of calculated over observed noise is less than was found to be the case with my tubes when I tested the formula in 1929 which Moullin and Ellis now propose. The experiments of other writers lead to the same results as did mine. In particular, Figs. 11 and 12 in a paper on "The Schottky Effect in Low-Frequency Circuits," by J. B. Johnson (*Physical Review*, 1925, vol. 26, p. 71) show a comparison between measured noise and calculations made in 1925 by the same formula as that now given by the present authors and illustrate the fact that the measured noise is far less than that predicted by the formula when adequate space charge is secured. Reference may also be made to the work of Hull and Williams (*Physical Review*, 1925, vol. 25, p. 147, Section 17 and Table 4), Thatcher and Williams (*Physical Review*, 1932, vol. 39, p. 472), and Thatcher (*Physical Review*, vol. 40, p. 114).

* Paper by Messrs. E. B. MOULLIN and H. D. M. ELLIS (see vol. 74, p. 323).

† "The Theory of the Schroteffekt," *Journal of the Franklin Institute*, 1925, vol. 199, p. 203.

‡ "Thermal Agitation of Electricity in Conductors," *Physical Review*, 1928, vol. 32, p. 110.

§ "A Study of Noise in Vacuum Tubes and Attached Circuits," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 243.

The chance of an electron getting past the space-charge barrier and reaching the plate depends on the initial velocity with which it left the filament and on the amount of space charge.

Variations in plate current are therefore determined by variations in the initial velocity and by variation in the space charge.

The first of these is related to the filament temperature by the Maxwellian distribution law. This introduces the factor kT .

The second is determined by the internal a.c. resistance of the tube.

Variations in plate current are determined solely by the filament temperature, and the a.c. internal resistance.

With the aid of this brief the form of the noise equations in the two cases can readily be inferred. Without space charge, the variational voltage set up by the fluctuating current is proportional to the external impedance $|Z|$. The mean square value of the variations resulting from perfectly random emission is proportional to the average value of the emission current I . Hence the mean square noise voltage is proportional to $I|Z|^2$, which is in accord with Fry's formula.

With complete space charge we have to deal with an impressed e.m.f. rather than with an impressed current, as was the case without space charge. The energy of this impressed e.m.f. is proportional only to the average energy of emission of the electrons, and hence to kT , where T is the filament temperature. The power expended by the impressed e.m.f. is proportional to the square of the e.m.f. divided by the resistive component of the impedance through which the resulting current flows. If, then, a short-circuit for alternating currents were placed across the vacuum tube, it follows by Thevenin's theorem that the mean square value of the effective internal e.m.f. would be proportional to the product of the impressed energy, kT , and the internal a.c. resistance of the vacuum tube. Hence the mean square value of the internal e.m.f. acting in the plate circuit and resulting from the initial velocities of the electrons is proportional to kTr , which is in accord with my formula, and agrees with the formula of Nyquist for a resistance r at the filament temperature.

When an external resistance R is connected to the vacuum tube, having, as the present authors agree, an effective internal e.m.f. proportional to kT_0R , the total e.m.f. around the circuit is the sum of the two impressed e.m.f.'s. In finding the mean square value of this, the authors question the validity of placing product terms of the form E_1E_2 equal to zero in any frequency interval df . They offer a possible explanation, based on the random character of the phase of E_2 with respect to E_1 , which is correct as far as it goes. In a more general sense the mean square value of the sum of two time functions which are individually independent of one another and which are of the "random" character indicated by the form of the equations is given, within a frequency interval df , by the simple sum of the mean square values of the two components taken separately. A commonly used example of this property occurs in textbooks on the theory of white light.

Coming now to the case of noise in the presence of

partial space charge, and the factor $\partial I_{av}/\partial I$ which the authors seem to have misunderstood, I first wish to express my appreciation of the remarks of Mr. C. L. Hirshman in the discussion.

The authors state that my view appears to be that "the pelting of the anode circuit by electrons produces *ipso facto* no effect. . . ." This is nearly, but not quite, a correct statement of my position. To show the slight difference, consider a stream of electrons proceeding across the vacuum tube at an exactly uniform rate, so that the interval between the arrival of any two successive electrons is the same for all. Under these conditions the current is the sum of the separate currents from each individual electron. The total current from a single electron is a pulse of some shape which starts at the time of the starting of the electron but which flows in all parts of a series circuit simultaneously, and not locally where the electron happens to be. The current from all of the electrons can be obtained by superposing the pulses from each individual electron. Each pulse has the same shape with respect to time as all the other pulses, however, and the time between the starting of any two successive pulses is the same. Hence, even though many pulses may have started before the first one has been damped out, the configuration will ultimately repeat itself every time a new electron starts. It therefore has a periodicity equal to the time between successive electrons. Moreover, this is the period of the lowest-frequency component present in the resultant current.

As an example, a current of 1 microampere represents the flow of 6.28×10^{12} electrons per second, and this would be the lowest of the fluctuation frequencies if the flow were exactly uniform.

It is consequently appropriate in noise studies to investigate the effects of variations from this precisely uniform flow. It is the variations from the uniform which produce the noise we are seeking, and not the pelting of the anode circuit by electrons.

The shot formula developed by Fry gives the mean square variation of the electrons emitted from the cathode. As remarked above, and pointed out by Hull and Williams* in 1925, the space charge tends to smooth out these variations and my factor $\partial I_{av}/\partial I$ is a measure of its success.

In Fig. 17 the present authors show curves of anode current and noise plotted as a function of anode potential, and state that for these curves "there is no change in filament temperature and hence no change of I or dI/dI_{av} ." Now, the factor $\partial I_{av}/\partial I$ which I have used is the slope of the curve of plate current versus total filament emission taken at the value of filament emission and plate potential actually employed. In mathematical form the factor is obtained by finding the variation in the functional equation

$$I_{av} = I_{av}(I, V_a)$$

so that

$$\delta I_{av} = \frac{\partial I_{av}}{\partial I} \delta I + \frac{\partial I_{av}}{\partial V_a} \delta V_a$$

This process is exactly analogous to the method of finding the variation in plate current resulting from

* *Physical Review*, 1925, vol. 25, p. 147.

variation in grid and plate potential. In this case we should have

$$I_{av.} = I_{av.}(V_g, V_a)$$

so that

$$\delta I_{av.} = \frac{\partial I_{av.}}{\partial V_g} \delta V_g + \frac{\partial I_{av.}}{\partial V_a} \delta V_a$$

Let us paraphrase the authors' statement from the standpoint of this latter relation. In place of Fig. 17 there would be a curve of some function of $I_{av.}$ (analogous to their noise curve) plotted against V_a . Their statement would now read "In this there is no change of grid potential and hence no change of V_g or $dV_g/dI_{av.}$."

This statement may or may not be true, depending on how one defines $dV_g/dI_{av.}$. It is evident, however, that $dV_g/dI_{av.}$ is not the reciprocal of $\partial I_{av.}/\partial V_g$ as defined in the variational equation above. It happens that $\partial I_{av.}/\partial V_g$ has been given the symbolism μ/r_a , while $\partial I_{av.}/\partial V_a$ is $1/r_a$, and the variational equation now reads

$$\delta I_{av.} = \frac{1}{r_a}(\mu V_g + V_a)$$

and no one would say here that because V_g happened to be held constant while V_a was varied in taking a set of data, it would follow that μ had the same value irrespective of V_a . In fact one of the important recent developments in vacuum tubes has been just such variable- μ tubes in which the variation in μ partly accounts for the characteristics of the tubes.

In an exactly analogous way, in the noise equation, the fact that I was held constant while V_a was varied does not mean that $\partial I_{av.}/\partial I$ was constant.

From a physical standpoint it is easy to see that the factor would not be constant, for $\partial I_{av.}/\partial I$ is a measure of the amount of space charge present, and this in turn is related to the anode potential whenever its value is sufficiently high to overcome the condition known as "complete" space charge, yet not so high as to obliterate the space charge entirely. The only safe way to determine the behaviour of the factor is actually to vary the filament temperature a slight amount and observe the behaviour of the plate current.

Several of the authors' figures contain curves of plate current plotted against filament current. In particular, Figs. 15, 16, and 20, may be cited. In none of these does the slope of the space-current curve approach zero. This being the case, it follows that the characteristics of the noise will qualitatively obey the kind of formula used by the authors, since $(\partial I_{av.}/\partial I)^2 I$ will vary in a rough way as does $I_{av.}$ when the space charge is incomplete as was the case in their tubes.

In conclusion, I hope that this communication has clarified any points in my paper which may have been obscure, and I anticipate that the present authors will find results more in accord with my views when they secure tubes capable of operating with more complete space-charge saturation of the filament.

Messrs. E. B. Moullin and H. D. M. Ellis (*in reply*): We are very grateful to Dr. Llewellyn for sending a contribution to the discussion of our paper. When our views have differed from those of Dr. Llewellyn we have commented in a spirit of friendly inquiry and not of dogmatic criticism: it is clear that Dr. Llewellyn has accepted these comments in the spirit in which they

were made, and we are very glad he has given a more detailed explanation of his views of this intricate problem. On the whole, we do not feel we are able either to accept or to rebut Dr. Llewellyn's views: the whole problem is intricate and obscure, and we do not feel that the experimental evidence is sufficient to clear the whole matter. We are not convinced that release from the space-charge barrier is perfectly regular, and we do not consider Dr. Llewellyn's exposition of this proposition to be conclusive. At the top of the second column of page 342 (vol. 74) we suggest that the difference of view is due to a different method of dividing the total effect into components, and we think that this is borne out by Dr. Llewellyn's tabular arrangement of effects with and without space charge. We have regarded the random pattering as being due to the variation of initial velocities, but we still do not see that this necessarily introduces an explicit factor kT . We have not succeeded in forming a mechanical picture of thermal agitation from Nyquist's derivation of the formula, whereas we have succeeded in forming such a picture from our own derivation from equipartition. Our derivation makes it hard for us to associate thermal agitation with an electron stream. We know no derivation of the expression for shot voltage which seems to us entirely satisfactory and for which the physical premises are not open to criticism. For example, what is there in our method of developing the expression which would be invalidated if the electrons arrived at the anode by conduction along a wire? Yet in such circumstances experience shows that the shot voltage is zero. We feel there should be some way of deriving the expression from the principle of equipartition of energy, if account is taken of the fact that the agitation velocity of the electrons is not a Maxwell distribution, because there is a specified average rate of arrival of electrons having super-normal energy. If this view should lead to the established expressions, we think that our difficulties, and, if we may say so, Dr. Llewellyn's difficulties, would disappear and both interpretations would be comprehended in a more general interpretation of the effect.

Since our paper was published, one of us has made further measurements to see whether V_s^2 is proportional to the joint impedance of the valve and circuit, in the condition of a constant average anode current and potential of the anode. There seems to be no possible doubt that in such circumstances V_s^2 varies as $[R\rho/(R + \rho)]^2$, and in this respect our formula (17) and the formula of Dr. Llewellyn are in complete agreement. Further careful tests, however, similar to those described by Fig. 22 and using a valve of the same type, showed that V_s^2 was not truly proportional to $I_{av.}$. As in Fig. 22, V_s^2 was proportional to $I_{av.}$ for currents between 3 and 12 mA, and in this range the value deduced for e was sensibly half the true value. For values of $I_{av.}$ less than 3 mA, however, it seemed that the departure from proportionality was greater than could be accounted for by uncertainty in the value of ρ . When $I_{av.}$ was 1 mA, the apparent value of e was 20 per cent in excess of the true value. We are obliged to Dr. Llewellyn for pointing out our misconception of the factor $\partial I_{av.}/\partial I$, used by him.

In conclusion, we wish once more to thank Dr. Llewellyn

for accepting our implied invitation to furnish more details of his picture of the physical mechanisms involved. We do not feel that the present state of knowledge is sufficient to prove that one picture is wrong and the other right, but we think that Dr. Llewellyn's contribution to the discussion will help readers of our paper to

form their own mental picture of these obscure effects. We hope before long to make more experiments which may help to clear up the difficulties, and we assure him that we shall approach such experiments with a perfectly open mind in respect to points where his view and ours have an apparent or real difference.

INSTITUTION NOTES.

Transmission Section.

The Council have set up a Transmission Section of the Institution for the reading and discussion of papers on the study, design, manufacture, construction, maintenance, and operation of transmission and distribution lines, both overhead and underground. This Section will be conducted on the lines of the existing Wireless Section and Meter and Instrument Section and will take the place as far as possible of the Overhead Lines Association, which, as the result of discussion with the Institution and a ballot of its members, will be dissolved.

Members of the Association who are already members of the Institution will automatically become members of the Transmission Section and will form its nucleus, together with those members of the Association who, although not at present members of the Institution, are subsequently elected into the Institution.

In addition, members of any class of the Institution may apply for membership of the Section. Such members must satisfy the Section Committee that they are actively engaged in the study, design, manufacture, construction, maintenance, and/or operation of transmission and distribution lines, and for this purpose they should complete and submit for consideration a membership application form. Copies of this form have already been sent to members of the Institution, and further copies may be obtained on application to the Secretary.

No supplementary subscription will be payable in respect of membership of the Section.

Due notice will be given of the meetings of the Section, which will commence next Session.

Scholarships.

The following Scholarships have been awarded for 1934:—

Ferranti Scholarship (Annual Value £250; tenable for 2 years).

F. C. Williams, M.Sc. (Manchester University).

Duddell Scholarship (Annual Value £150; tenable for 3 years).

S. I. Hollingworth (Chipping Campden Grammar School).

Silvanus Thompson Scholarship (Annual Value £100, plus tuition fees; tenable for 2 years).

S. G. Bittles (Messrs. Harland & Wolff, Ltd., Belfast).

Swan Memorial Scholarship (Value £120; tenable for 1 year).

E. Bradshaw, M.Sc. (Royal Technical College, Glasgow).

David Hughes Scholarship (Value £100; tenable for 1 year).

W. B. Hutchison (Royal Technical College, Glasgow).

Salomons Scholarships (Value £50 each; tenable for 1 year).

R. Bernard (Heriot Watt College, Edinburgh).

W. McStravick (Heriot Watt College, Edinburgh).

Thorrowgood Scholarship (Annual Value £25; tenable for 2 years).

K. N. Fordham (London, Midland and Scottish Railway Co.).

I.E.E. Regulations for the Electrical Equipment of Buildings.

A revised Edition (Tenth Edition) of the above Regulations has been approved by the Council and has just been published. Copies can be obtained at the offices of the Institution or from the publishers, Messrs. E. and F. N. Spon, Ltd., 57 Haymarket, London, S.W.1, at the following prices:—

Bound in cloth, 1s. 6d. net (or 1s. 9d. post free).

Bound in paper covers, 1s. net (or 1s. 2d. post free).

War Thanksgiving Education and Research Fund (No. 1).

Grants of £50 each have been made for 1934–1935 to the following for research purposes:—

R. R. C. Rankin (Royal Technical College, Glasgow).

H. Walton (King's College, London).

Proceedings of the Wireless Section.

113TH MEETING OF THE WIRELESS SECTION, 7TH MARCH, 1934.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 7th February, 1934, were taken as read and were confirmed and signed.

A paper by Mr. W. F. Rawlinson, D.Sc., Associate

Member, entitled "The Reception of Wireless Signals in Naval Ships" (see page 293), was read and discussed.

At the conclusion of the discussion Mr. W. E. Benham, B.Sc., Associate Member, gave a demonstration of a low-voltage electron microscope. [A Note on the subject appears on page 388.]

The meeting terminated at 8 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

114TH MEETING OF THE WIRELESS SECTION, 11TH APRIL, 1934.

Mr. G. W. N. Cobbold, M.A., Vice-Chairman, took the chair at 6 p.m.

The minutes of the meeting held on the 7th March, 1934, were taken as read and were confirmed and signed.

A paper by Mr. P. P. Eckersley, Member, entitled "Principles of Audio-Frequency Wire Broadcasting" (see page 333), was read and discussed.

The meeting terminated at 8.10 p.m. with a vote of thanks to the author, which was moved by Mr. Cobbold and carried with acclamation.

115TH MEETING OF THE WIRELESS SECTION, 2ND MAY, 1934.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 11th April, 1934, were taken as read and were confirmed and signed.

The Chairman announced that the following members had been nominated to fill the vacancies which would occur on the Committee on the 1st October, 1934:—

Chairman: S. R. Mullah, M.B.E.

Vice-Chairman: T. Wadsworth, M.Sc.

Members of Committee: N. F. S. Hecht, J. Joseph, Frederick Smith, and C. E. Strong, B.A.

In the event of a ballot for the new Committee being required, Messrs. J. F. Herd and H. J. Lucas were appointed scrutineers.

A paper by Commander J. A. Slee, C.B.E., R.N., Member, entitled "An Examination of the Causes and Nature of the Interference to which the Wireless Communications of the Mercantile Marine are Subjected" (see page 355), was read and discussed.

The meeting terminated at 7.48 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

Lending Library.

A new edition of the Lending Library Catalogue has been published. Copies can be had on application to the Secretary.

Accessions to the Reference Library.

[NOTE.—The books cannot be purchased at the Institution; the names of the publishers and the prices are given only for the convenience of members. (*) denotes that the book is also in the Lending Library.]

EVE, A. S., C.B.E., D.Sc., F.R.S., and KEYS, D. A., M.A., Ph.D. Applied geophysics in the search for minerals. 2nd ed. 8vo. x + 296 pp. (Cambridge: University Press, 1933.) 16s.

FALLOU, J. Courants de court-circuit. sm. 8vo. 180 pp. (Paris: Librairie J. B. Baillièrre et Fils, 1933.) 27 francs.

FENNELL, W. A review of the Grid Scheme, its inception and operation. fol. 24 pp. (London: Electrical Press, Ltd.) 2s. 6d.

GALL, D. C. Railway track-circuits. A book for railway signal engineers and all concerned with the theory and design of circuits. 8vo. xvi + 231 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1933.) 7s. 6d. (*)

GEMANT, A., Dr. Liquid dielectrics. Transl. by V. Karapetoff. 8vo. ix + 185 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1933.) 18s. 6d.

GIBSON, C. R., LL.D. Electrical conceptions of to-day. 8vo. 284 pp. (London: Seeley, Service and Co., Ltd., 1933.) 6s. (*)

GLOVER, C. W. Practical acoustics for the constructor. 8vo. xi + 468 pp. (London: Chapman and Hall, Ltd., 1933.) 25s. (*)

GOLDING, E. W. Electrical measurements and measuring instruments. A textbook covering the syllabuses of the B.Sc. Engineering, City and Guilds (Final), and A.M.I.E.E. examinations in this subject. 8vo. x + 794 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1933.) 20s. (*)

GRAY, A., M.Sc., and WALLACE, G. A., M.Sc. Principles and practice of electrical engineering. 8vo. xiii + 538 pp. (New York, London: McGraw-Hill Book Co., Inc., 1933.) 24s. (*)

GRIFFITHS, R., M.Sc. Thermostats and temperature regulating instruments. 8vo. 157 pp. (London: C. Griffin and Co., Ltd., 1934.) 10s. 6d. (*)

GRIMSEHL, E. A textbook of physics. Ed. by R. Tomaschek. Transl. by L. A. Woodward. vol. 3, Electricity and magnetism. 8vo. xiv + 685 pp. (London: Blackie & Son, Ltd., 1933.) 25s. (*)

GUILBERT, C. F. Essais des machines électriques. 2nd ed. 8vo. viii + 535 pp. (Paris: Librairie J. B. Baillièrre et Fils, 1934.) 95 francs.

HARNWELL, G. P., Ph.D., and LIVINGOOD, J. J., Ph.D. Experimental atomic physics. 8vo. xiii + 472 pp. (New York, London: McGraw-Hill Book Co., Inc., 1933.) 30s. (*)

HARRISON, H. H., M.Eng., and PREIST, T. P. Automatic street traffic signalling. (Apparatus and methods). With a foreword by Sir H. P. Maybury. 8vo. x + 187 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1934.) 12s. 6d. (*)

HÉMARDINQUER, P. Les lampes de T.S.F. modernes et leur utilisation. 8vo. 126 pp. (Paris: Etienne Chiron, 1933.) 10 francs.

HENNEY, K., M.A. Principles of radio. 2nd ed. 8vo. xii + 491 pp. (New York: J. Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1934.) 21s. 6d. (*)

HOFMAN, H. O., Ph.D., and HAYWARD, C. R. Metallurgy of copper. 2nd ed. 8vo. xiii + 419 pp. (New York, London: McGraw-Hill Book Co., Inc., 1924.) 30s.

HORWOOD, W. L. Electrical technology. 8vo. xii + 347 pp. (London: Charles Griffin and Co., Ltd., 1933.) 10s. 6d. (*)

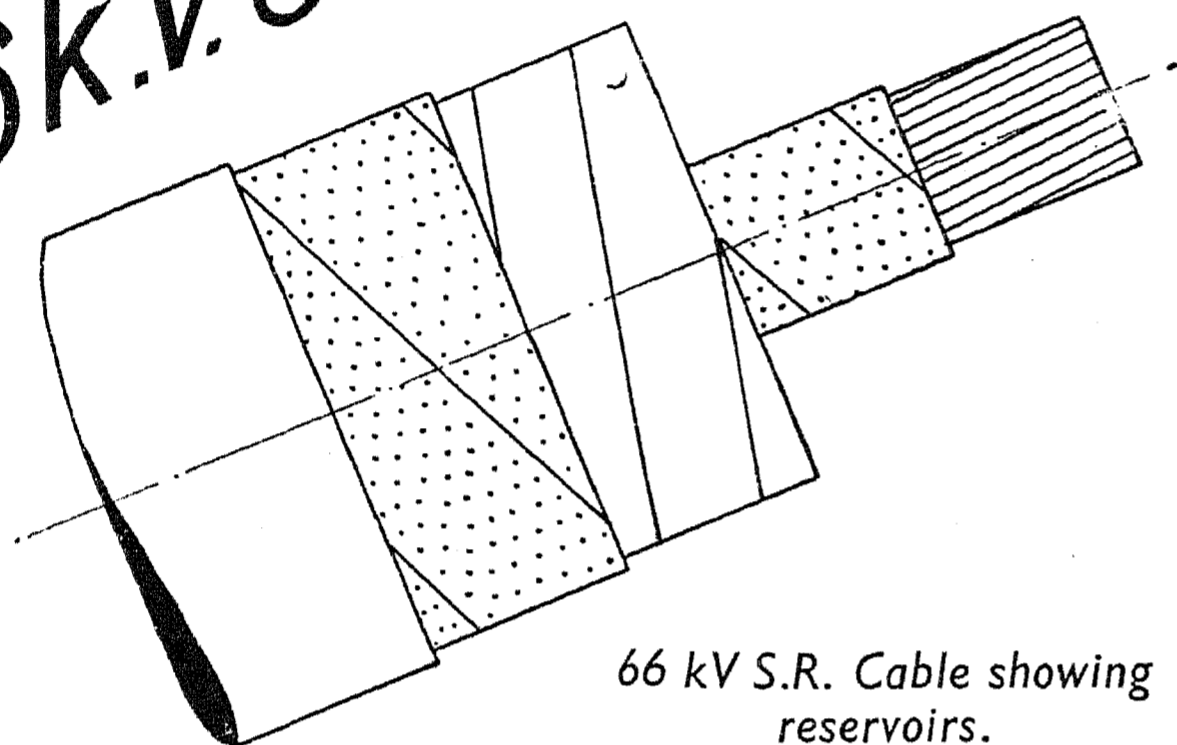
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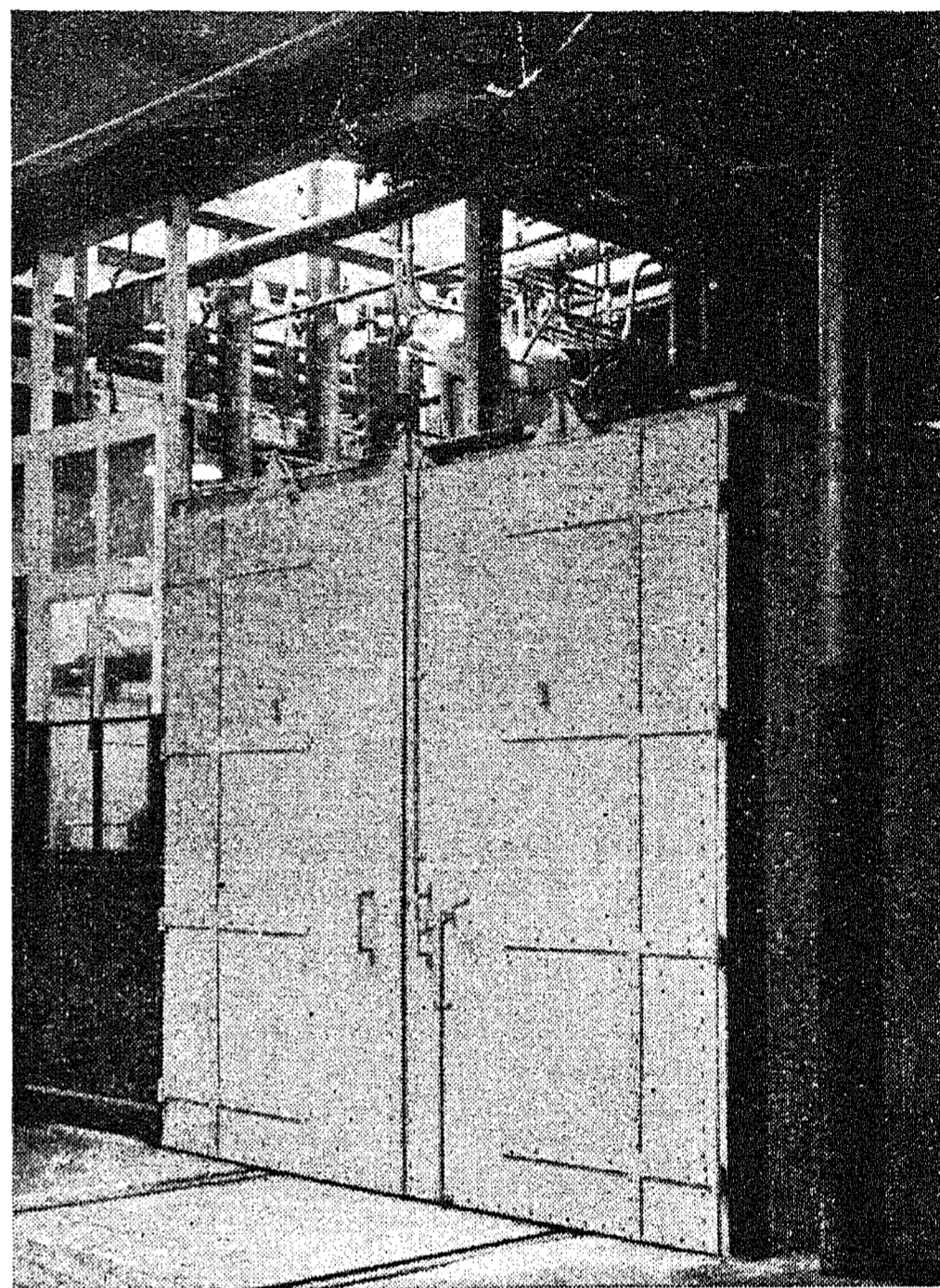
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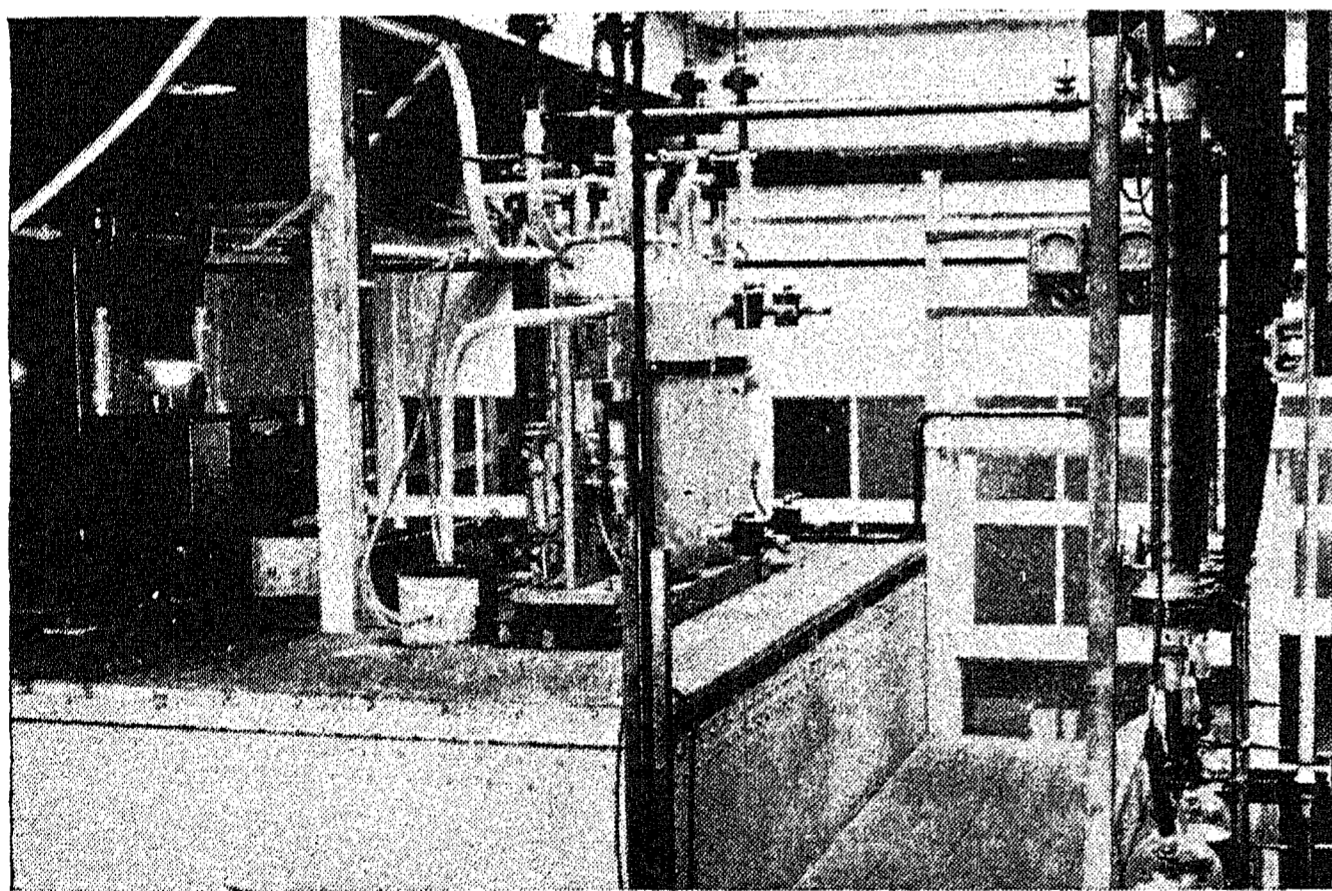
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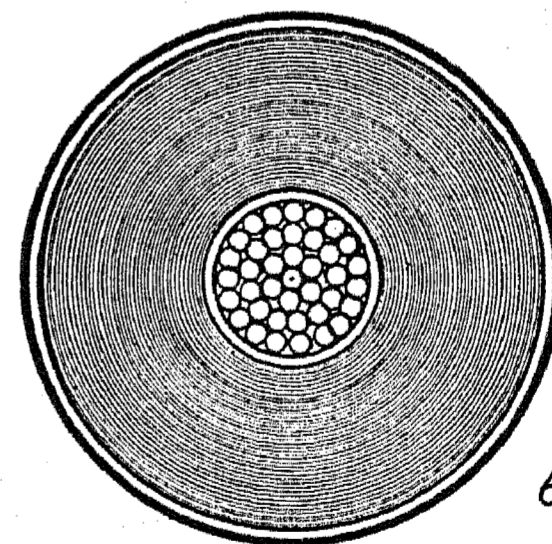


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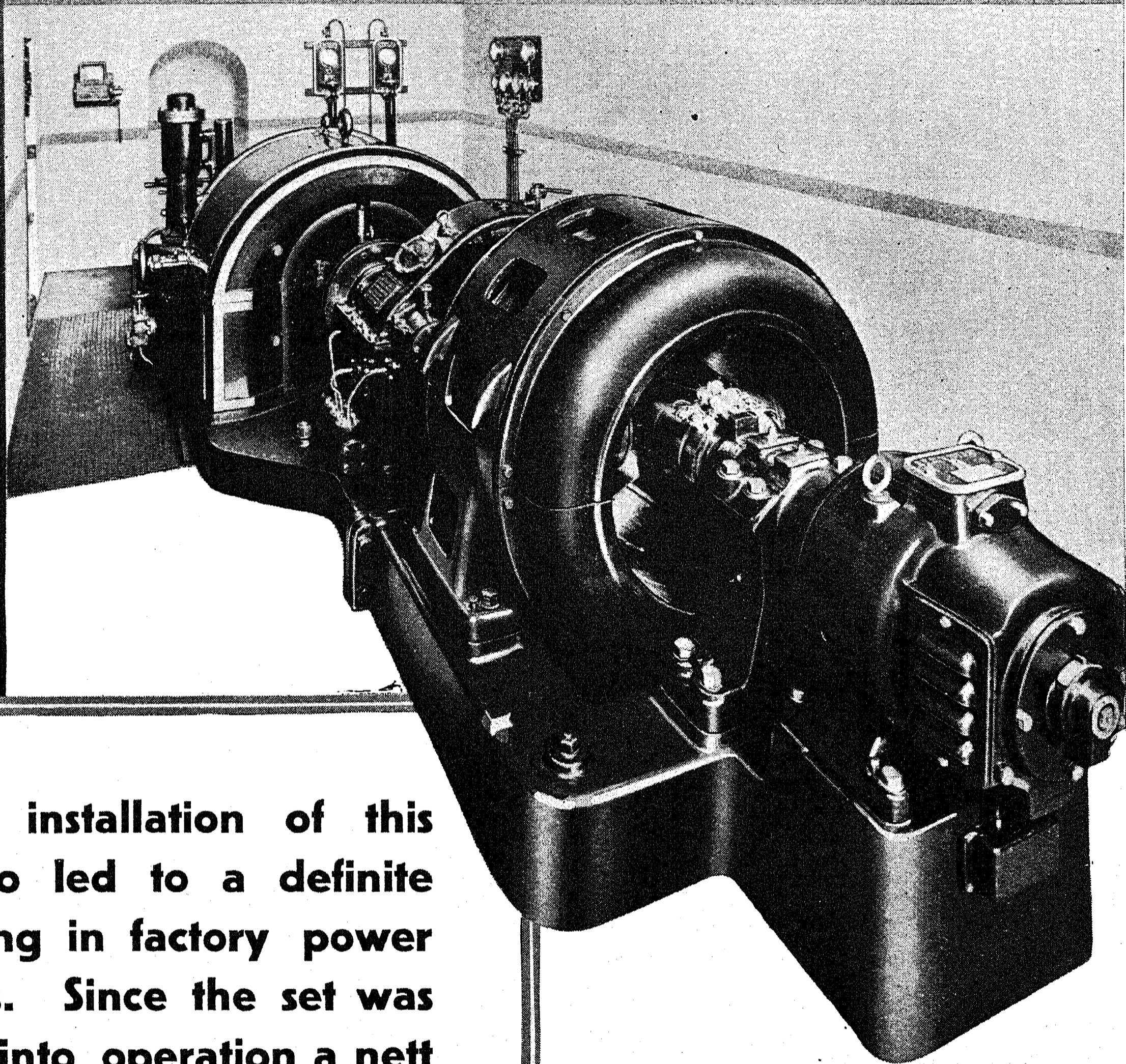
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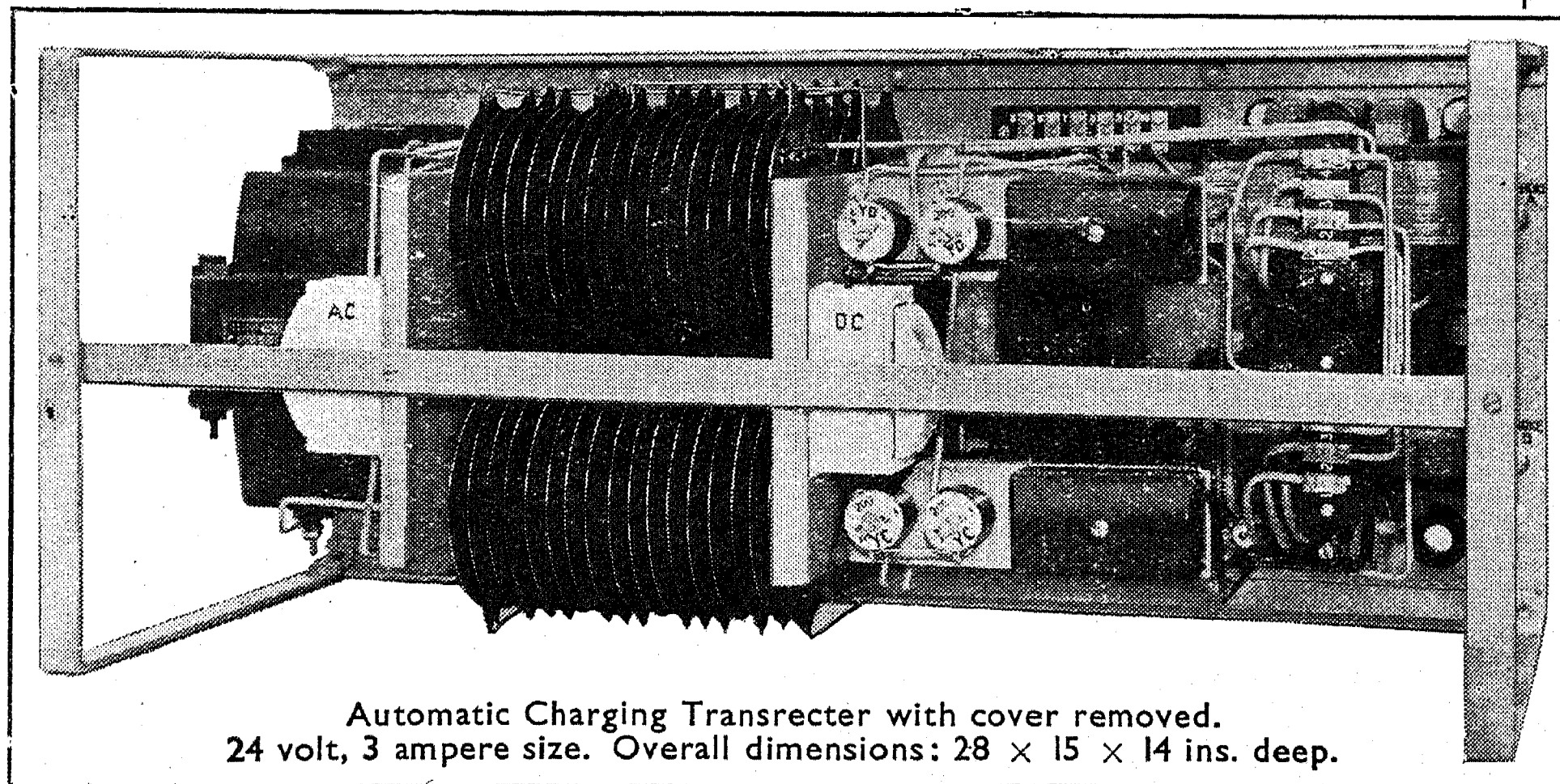
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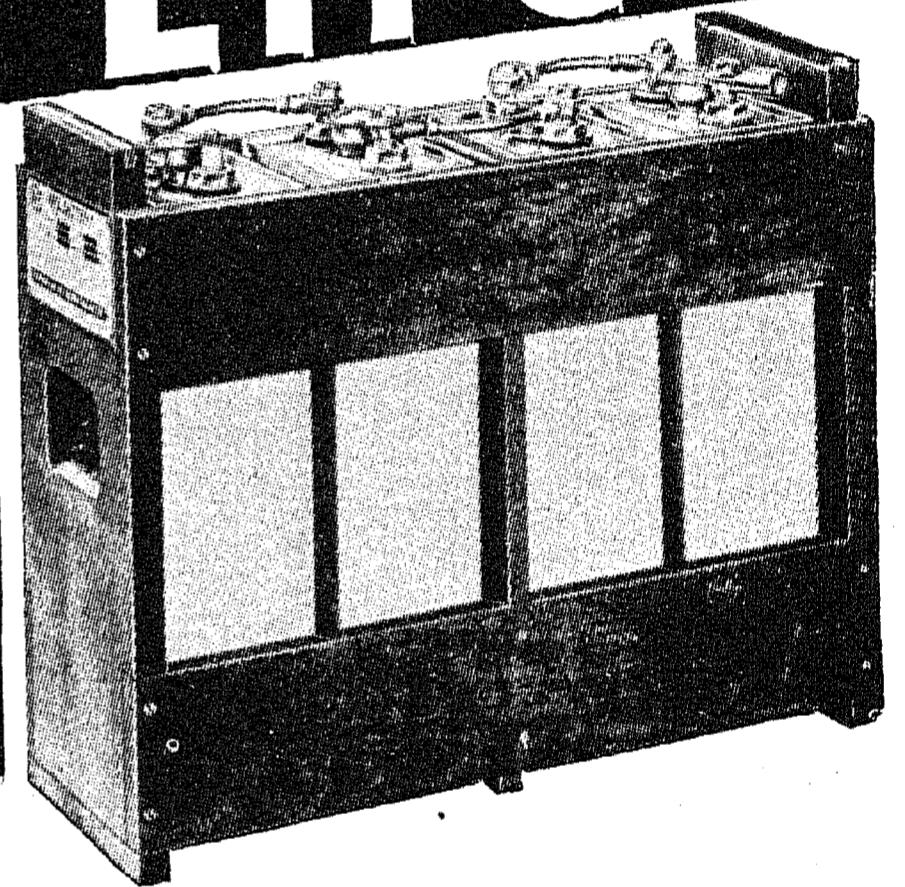
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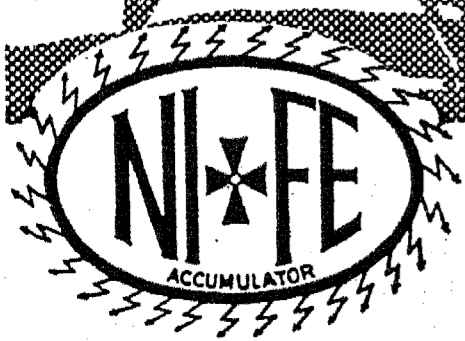
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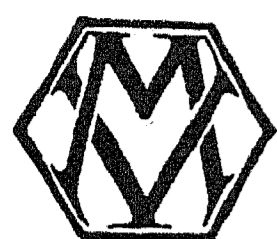
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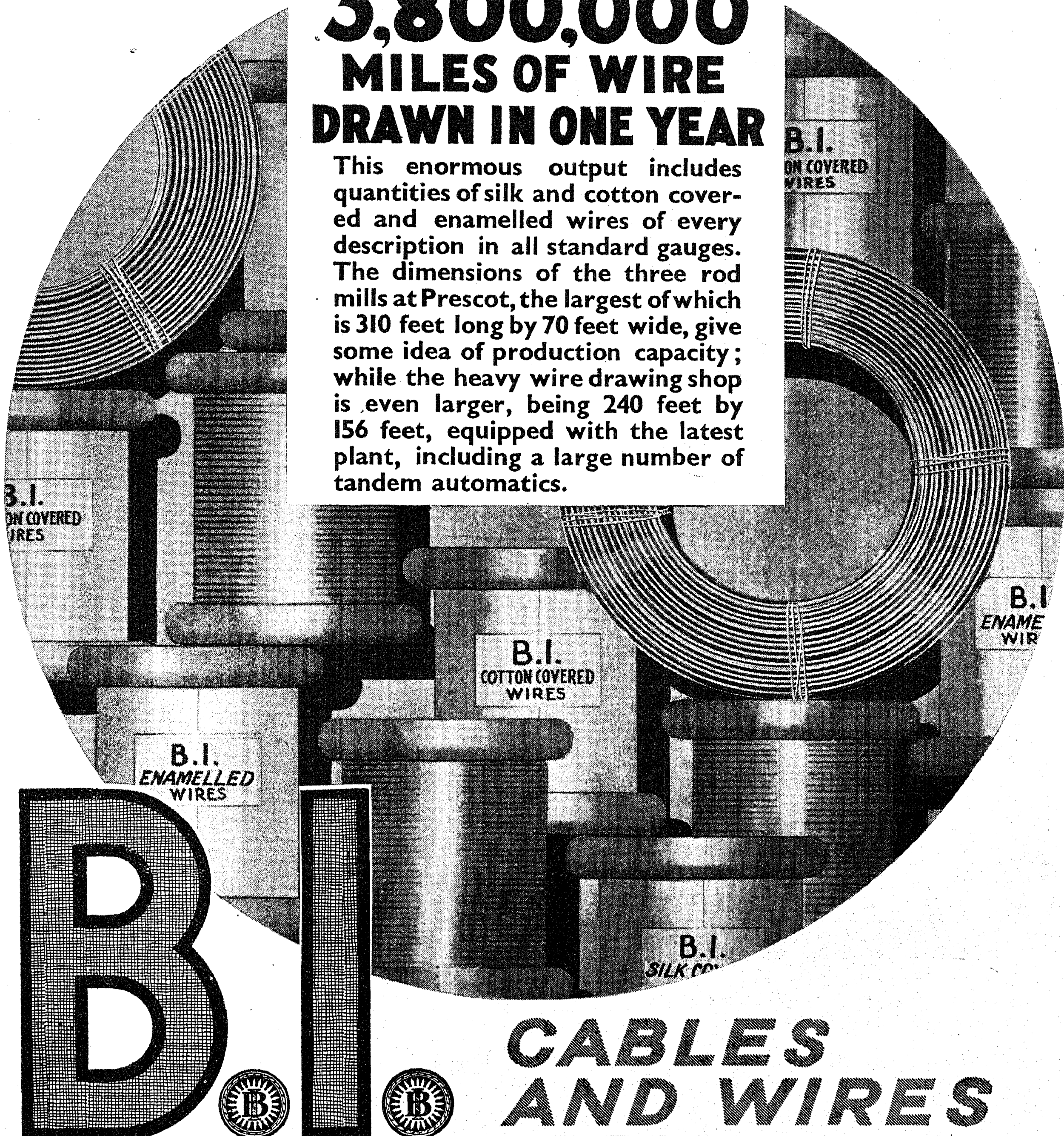
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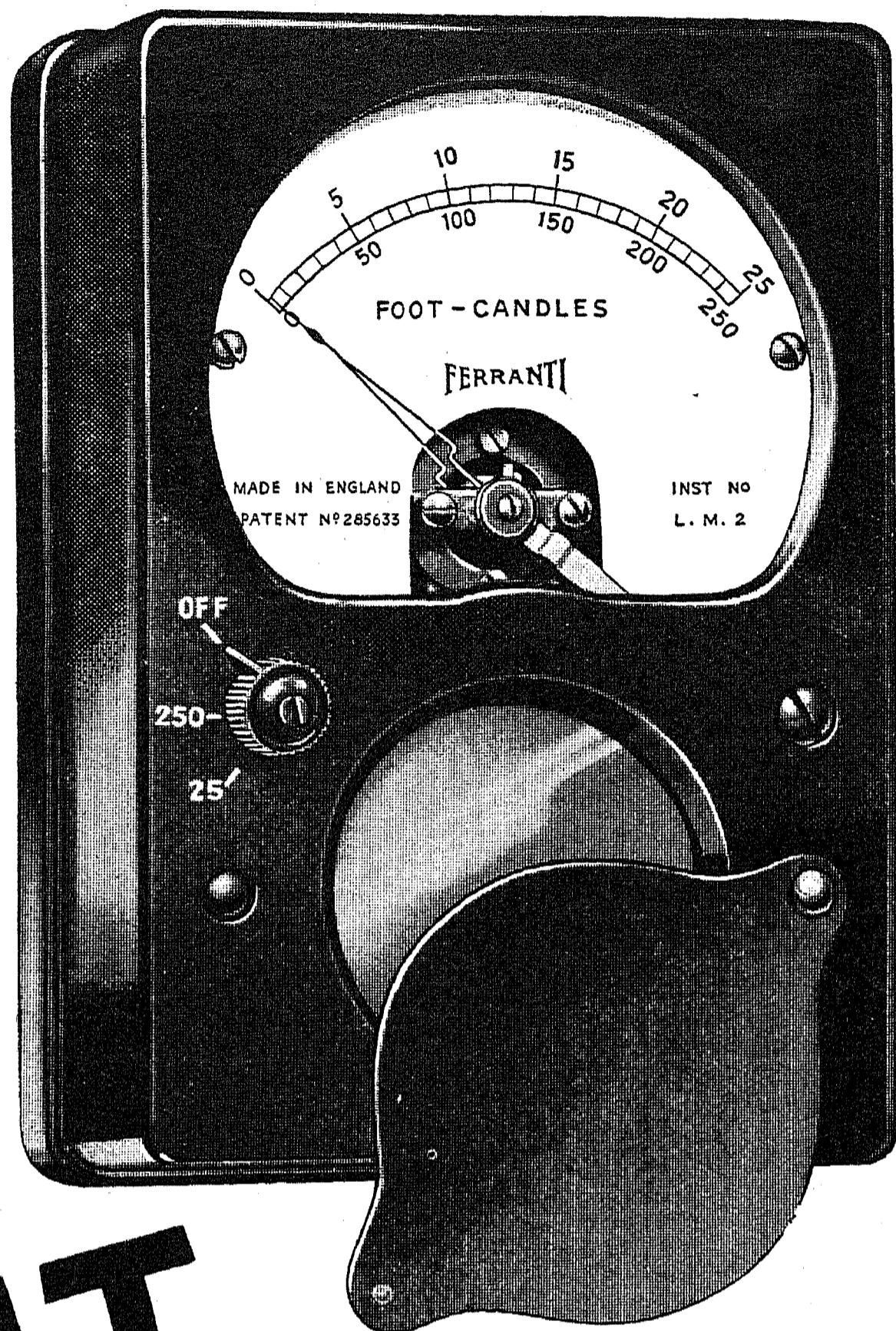
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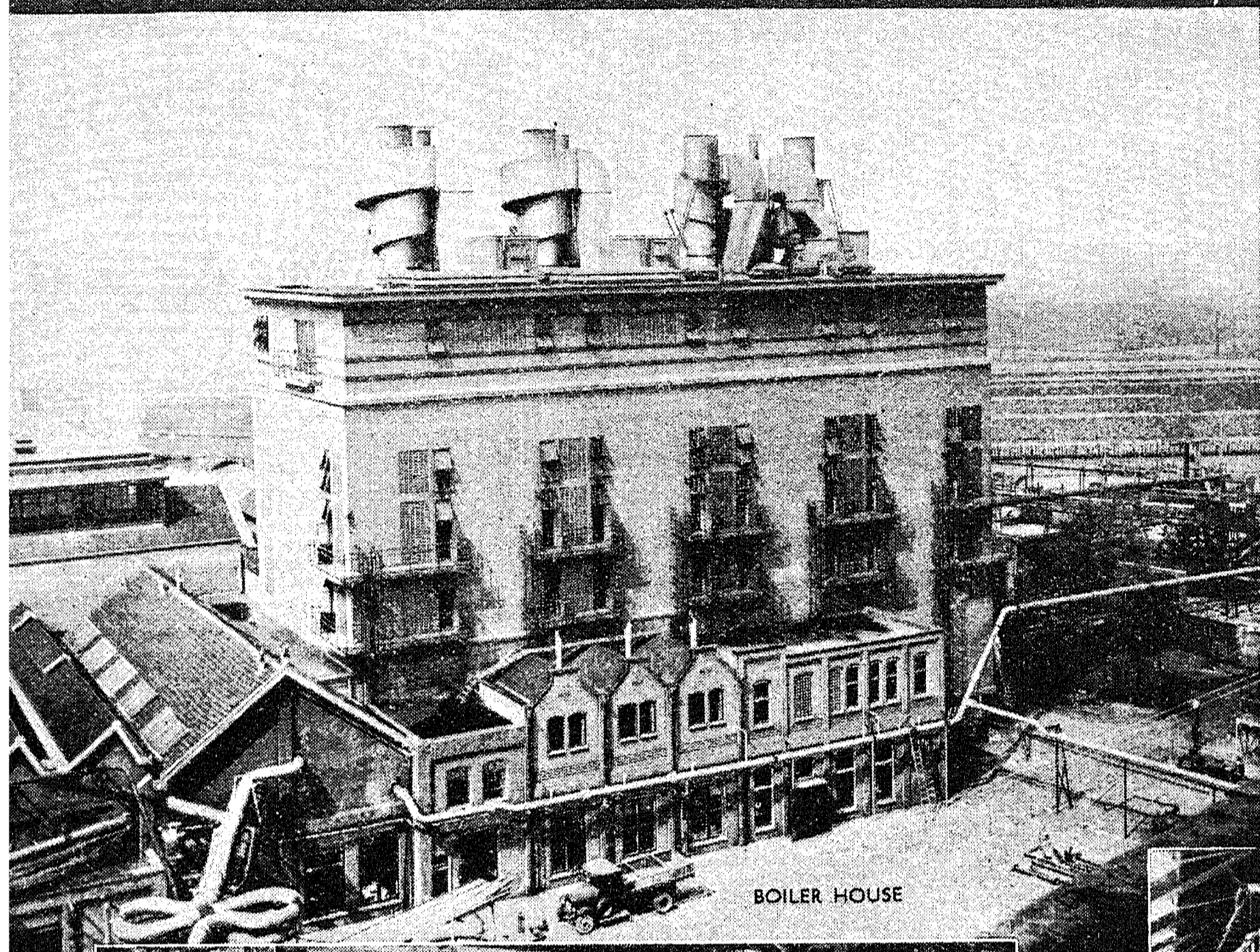
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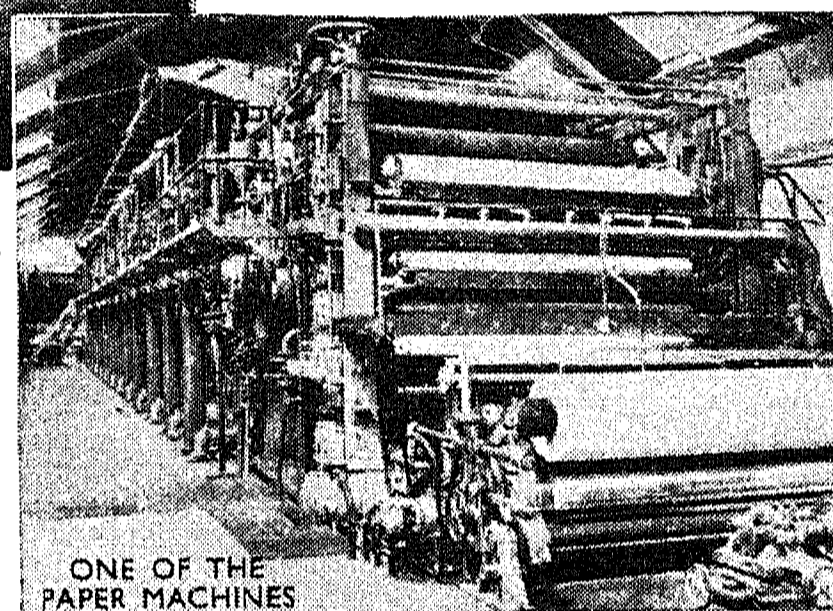
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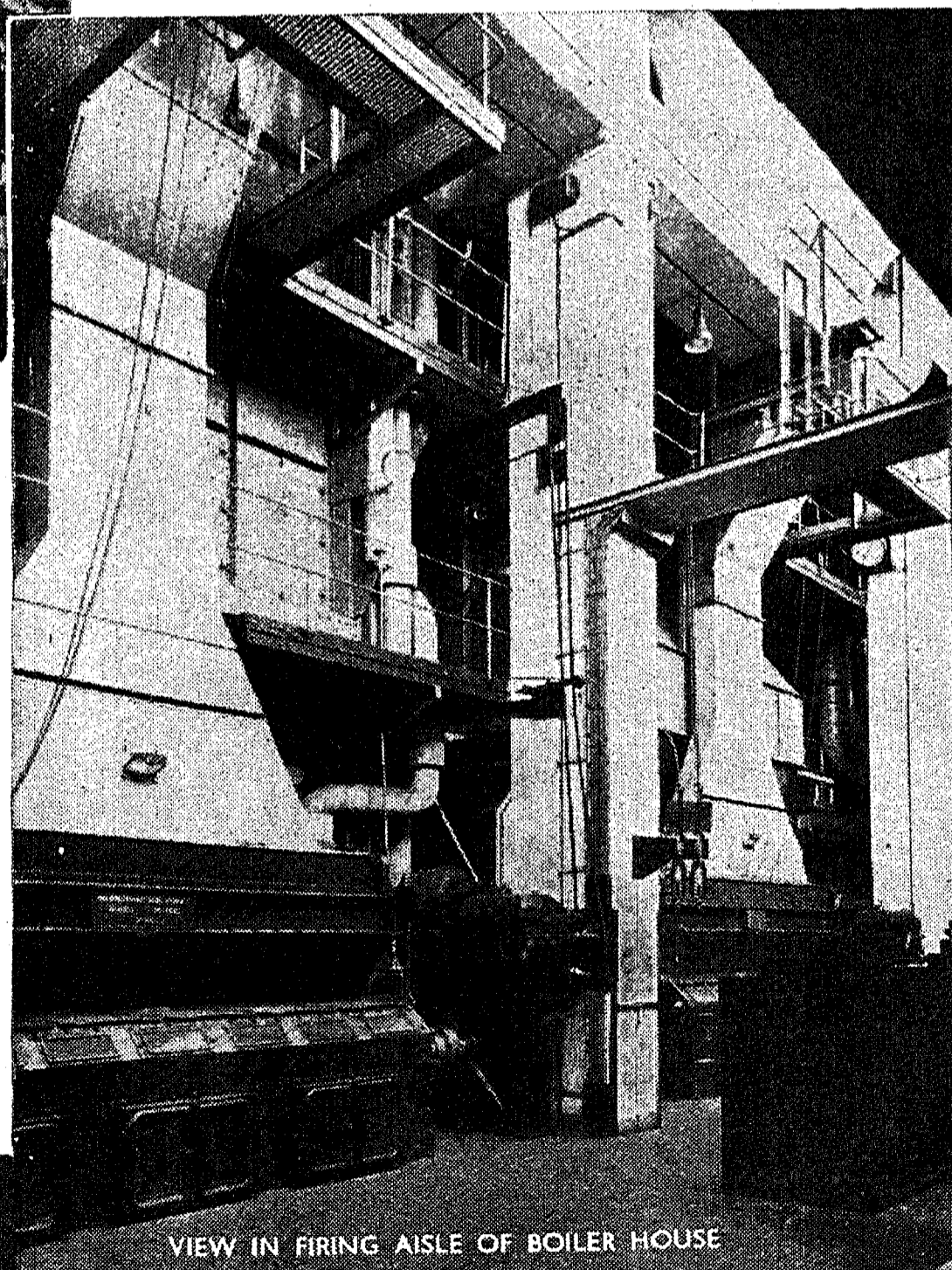
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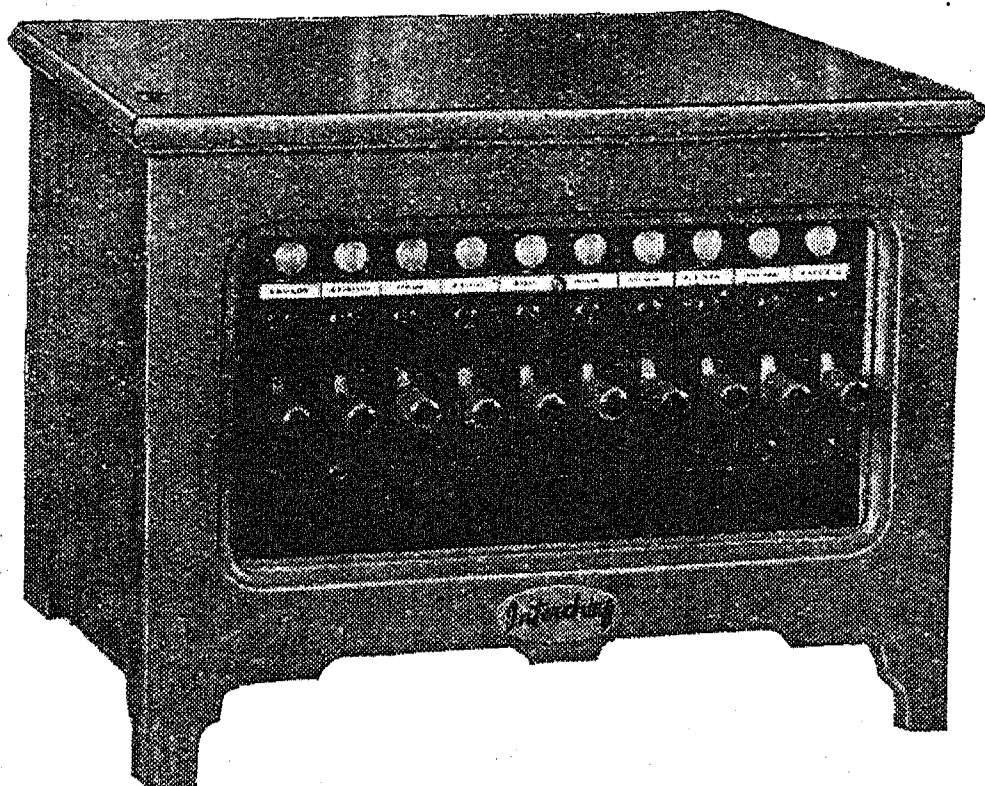
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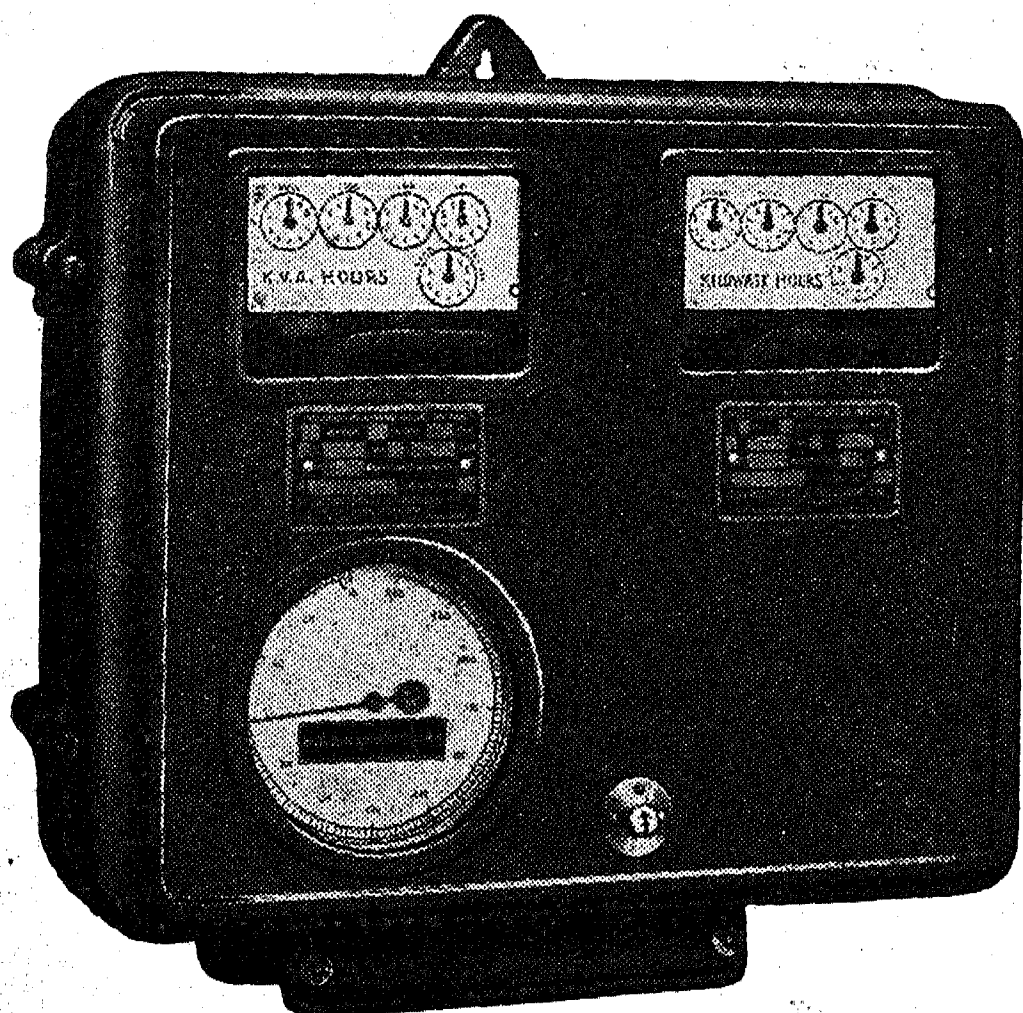


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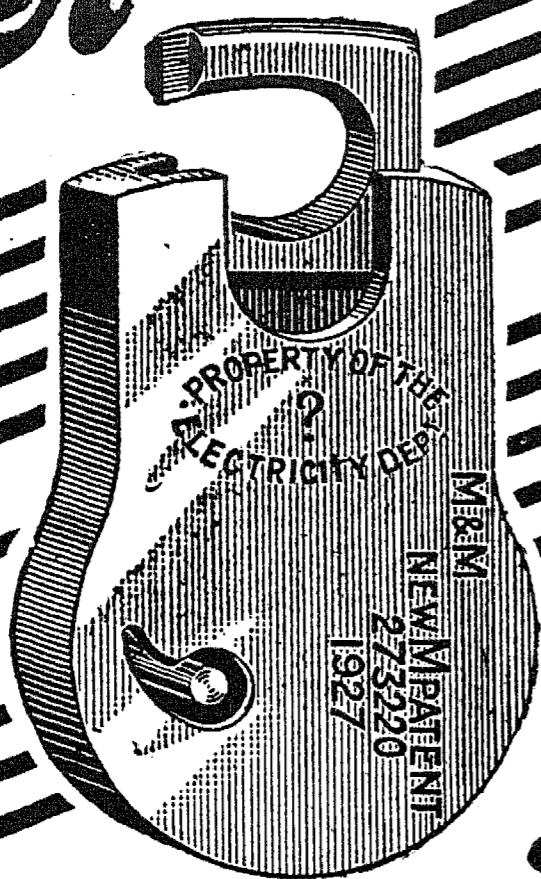
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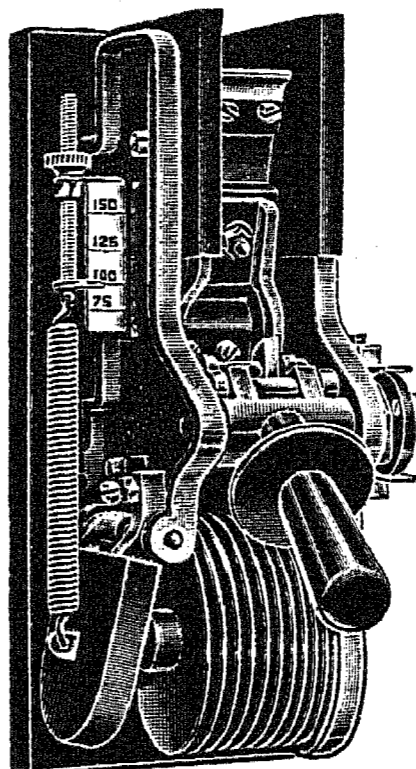
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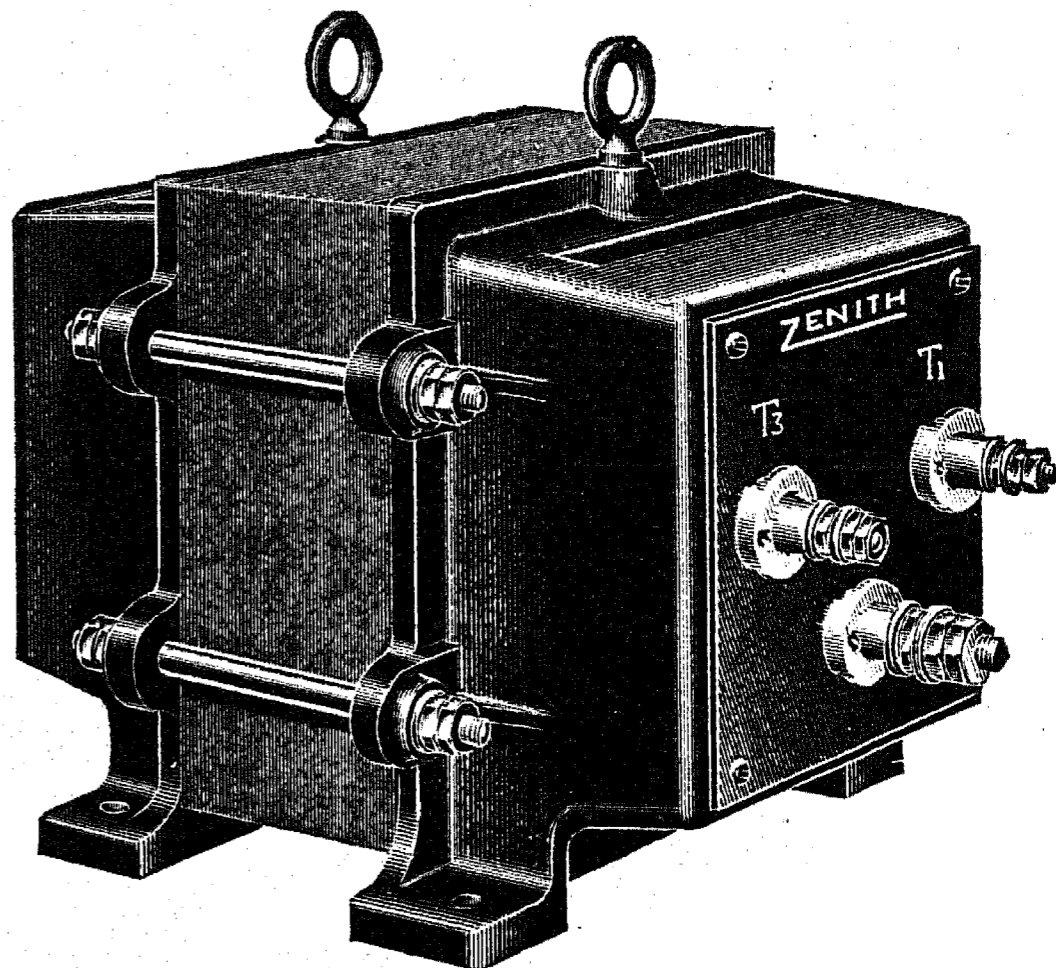
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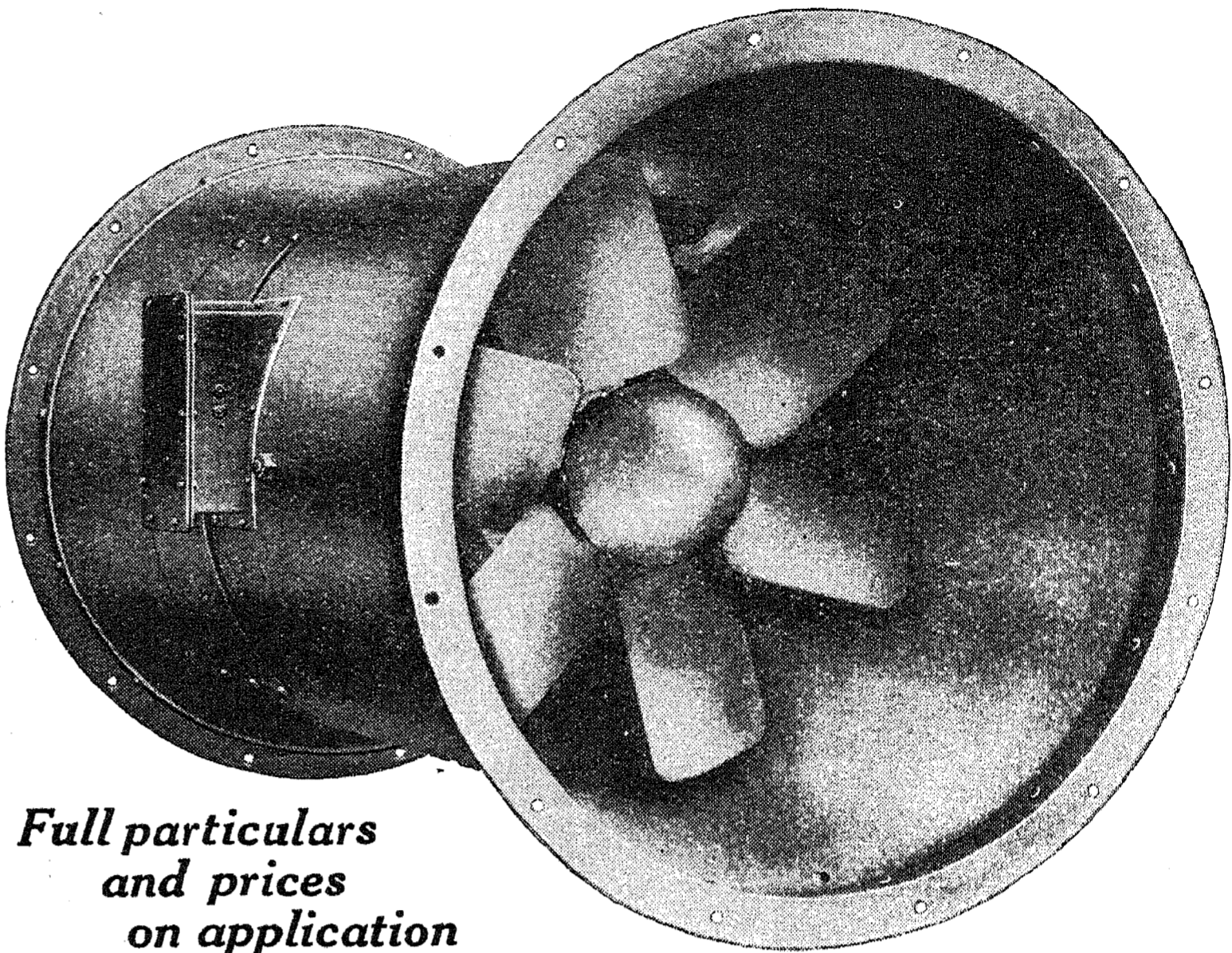
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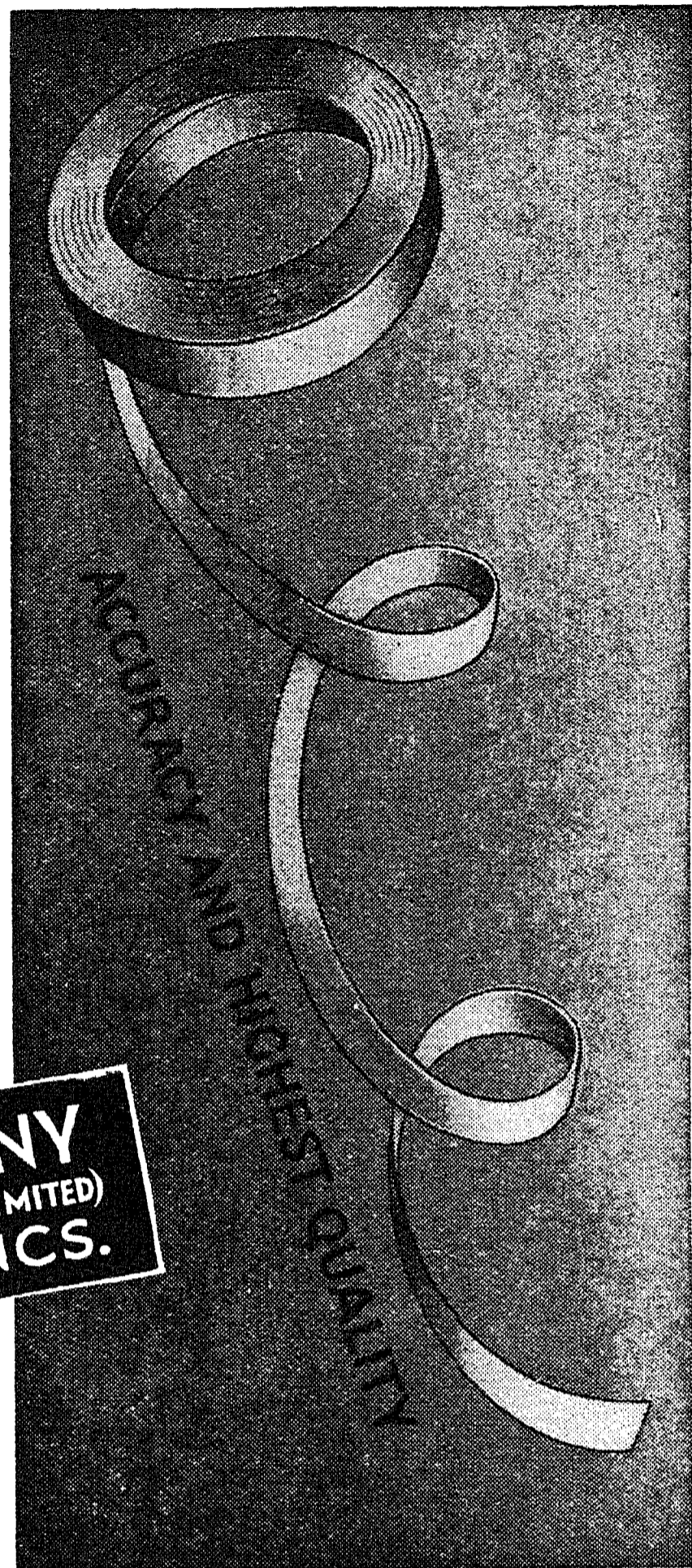
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